PLANT3D

Sponsor: Rory Aronson

FarmBot Trackless Redesign Final Report

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Statement of Disclaimer

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Executive Summary

For this project the team PLANT3D worked along with Rory Aronson and FarmBot to generate a cheaper more user-friendly design for the FarmBot Genesis 1.3. Working with Rory and FarmBot, we as a team generated a list of design requirements and engineering specifications for the project. These requirements centered around creating a more accessible FarmBot model for the average person to be able to purchase and set up with ease. Much of this required taking the existing system and eliminating the most common problem areas. These were the track system, built using 1.5 meter aluminum extrusions and the complex interchangeable tooling system.

Identifying the two main problem areas in the design allowed us to focus on potential solutions. With many potential systems looked at and analyzed the best ones to come out of the brainstorming process were a timing belt system that could exist directly on top of the raised bed and an all-in-one tool head system that could eliminate the need for constant changing of different tool heads. Several other designs were experimented with but ultimately were deemed to impractical or complex to reasonably fulfill the design requirements.

Through multiple iterations of designs an ideal shape and layout of the wheel plates was developed. This design featured an edge which could reach below the edge of the raised bed and act as a hard stop from the FarmBot main gantry falling off either side of the raised bed. This also led to the design of aluminum end stops being placed along the corners of the raised bed in order to prevent the FarmBot gantry from running off of the ends of the bed. A double wheel design was implemented, not only to help improve the allowable deviations in the bed sides, but to provide a groove for the timing belt to easily pass. Along with the groove two idler pulleys were added onto the wheel plate to help in guiding the timing belt to the stepper motor pulley.

The tool head was designed to take all the functionality of the different FarmBot tools and put them onto one tool head. In order to fit everything into one space the same size as one of the old tools, several of the components were replaced with higher quality sleeker alternatives. A new anti-clog water nozzle was added to replace the old plastic shower head. This nozzle also acts as a double for the weeder to save on space. The same Luer Lock and soil sensor were placed onto this tool head to maintain their functionality.

By making these design changes costs of the system were significantly decreased. The combination of drive and tool system savings is almost 30%. The part count was reduced by over 65% by eliminating lots of small redundant parts. These changes also greatly reduced overall weight and complexity of the system. Testing the performance of our design showed no significant loss in function of the FarmBot. Precision remained within 2cm of targets everywhere around the raised bed.

All but one of the parts of our new design are through current FarmBot vendors. The only new vendor is a plastic machining company manufacturing the delrin spacers. All the other custom parts will be waterjet cut by BigBlueSaw. The rest of the design is made from standard parts purchased through Open Builds and McMaster Carr. Moving forward this design shows that FarmBot could succeessfully operate as a more simplistic system, riding directly on top of a raised bed using only one tool head without any significant loss in precision or functionality.

Introduction

FarmBot is the world's first multifunctional farming system that can be pre-programed to plant, water, de-weed, and detect soil moisture levels in a raised-garden bed (Figure 1). FarmBot operates via a gantry system that moves on 2 tracks which require parallelism within 1mm (Figure 2). According to CEO Rory Aronson, over 500 FarmBot's have been purchased in 2017 by a variety of clientele ranging from horticulturists at NASA who plan to use FarmBot to run farming simulations on Mars, to K-12 schools who want to teach students about nutrition, robotics, and agriculture. Since FarmBot's market release, one of the most common customer complaints is the complexity of setting up the tracks to be parallel within the required 1mm. Rory Aronson has reached out to PLANT3D to develop a new version of FarmBot that can increase the current tolerance of 1mm to 1cm Rory believes that a more accessible version of FarmBot will help FarmBot evolve from its current image as a tedious home project to a user friendly home appliance. PLANT3D's first goal is to design a flexible tracking system that FarmBot's existing gantry can function on. This new tracking system will require a new tool head to be designed to account for an increased tolerance within the system.

Rory Aronson, founder and owner of FarmBot, is the primary stakeholder for this project along with the other FarmBot employees. Additional stakeholders will be anyone who purchases FarmBot, with the idea that this project will make FarmBot more accessible to the average homeowner. This will change FarmBot's typical consumer to someone less tech savvy who is looking for more of an appliance when buying FarmBot. The members of PLANT3D as a project group are also stakeholders who are looking to both improve FarmBot as a product and apply and learn new engineering skills through this project. Karla is an additional stakeholder as the one advising the project and will ultimately be judging its success and the success of the group.

Figure 1: The Original FarmBot

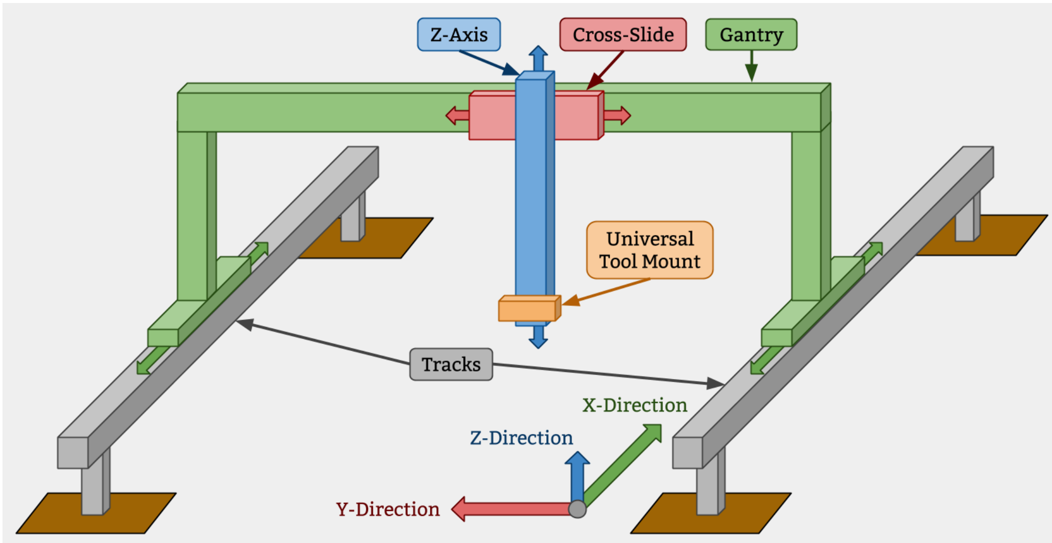


Figure 2: This shows the basic layout of FarmBot and shows what the basic parts are.

Project Management Plan

The project began with making the PLANT3D team out of engineering students in the 2017-2018 Cal Poly interdisciplinary senior project course. A team contract was made and signed by all members affirming they abide to act respectfully; the team contract can be seen in Appendix F. The PLANT3D team researched and identified engineering specification requirements the final design must abide by to be considered a successful project. A Gantt chart was made to schedule project progress such as important milestones, design reviews, manufacturing deadlines, and testing plans. The engineering requirements were kept in consideration while building conceptual prototypes and brainstorming. The brainstorming included using Pugh charts to compare designs against one another and weigh the benefits and costs of each design. Once the brainstorming and rapid conceptual prototyping led the PLANT3D team to converge on a few designs, a conceptual design review was held with the Interdisciplinary senior project class, advisors, and sponsor.

The feedback from the conceptual design review was used to narrow down the conceptual ideas to a few strong concepts. Then the PLANT3D team began to manufacture their first prototype. This included procuring standard parts, such as an existing FarmBot, a variety of wheels, and stock to create wheel plates out of. An all-in-one tool head was 3D printed, and a testing plan for the prototype was created. Then, the first complete prototype was assembled and demonstrated at the critical design review held with the interdisciplinary class, advisors, and sponsor. This provided essential feedback to the PLANT3D team, including sponsor preference of a timing belt driven system.

After the critical design review, the design was adjusted and improved. The new design was manufactured with consideration into manufacturing techniques and efficiency. A hardware demonstration was performed, and the software was developed using FarmBot's web interface application. The design was adjusted to optimize performance and testing was performed of the entire system to affirm the design met the engineering specifications. The project was presented to the public on June 1, 2018 at the Cal Poly Senior Project Expo. This report was then finalized to record the work team PLANT3D made towards a successful drive system that eliminated tracks.

Background and Information Gathering

According to Rory, 15 prototypes of FarmBot have been designed over the past 5 years. However, only FarmBot V1.3 is currently available on the market for purchase at a price of $2,600 dollars. Last year, Rory worked with an interdisciplinary team at Cal Poly to devise a version of FarmBot that operates on polar coordinates rather than the original version which is based on Cartesian coordinates.

FarmBot Inc. is a California Benefit Corporation and openly shares its products and business. FarmBot hardware designs are released in accordance with the Open Source Hardware Association's definition of open source hardware and the software source code is released under a permissive license approved by the Open Source Initiative.

FarmBot's website provides thorough documentation of all the required parts needed to assemble FarmBot with step-by-step video and written instructions. FarmBot is comprised of both off-shelf and manufactured parts, which can only be purchased through FarmBot. FarmBot's manufactured parts include the four tool heads, tool mount, tool holder, and the brackets used to fasten the current track system to the raised bed.

FarmBot's software is accessed from a web application at my.FarmBot.io and is where FarmBot owners can control and configure FarmBot to meet their garden's needs. FarmBot relies on the customer having access to sources of water, electricity, and internet that are standard features of a small home. Features not included in the FarmBot kit are the raised bed, extension cord, and garden hose.

Design Requirements

The specifications listed are based upon Rory's recommendations, but will be refined and adjusted based on testing during the design phase of the project. According to Rory, most users take anywhere from 20-40 hours to assemble FarmBot and he would like to decrease the assembly time to under 15 hours. The current model requires an accuracy of 1 mm in order for the gantry system to select the different tool heads from the tool holder. Since we are increasing the allowable tolerance for the system to operate, the gantry will not be precise enough to grab tool heads from the tool holder. Therefore, a new tool head will be required. Rory would like to reduce the cost to ship FarmBot to customers which is why we will aim to reduce the shipping weight and size as an added benefit.

For the gantry to support the tool head, Rory indicated that the tool head must be under 2lbs. The necessary features to include in the tool head are to plant seeds, water, and de-weed. The seeding portion of the tool head should accommodate multiple seed sizes, which FarmBot does currently with different needle sizes in a Luer Lock system. Rory expressed that a soil moisture sensor is an expendable feature but would like to integrate the feature if possible. The height of the tool head must be 0.5 meters above the soil level because the maximum plant height is 0.5 meters.

In order to make the system the best it can be, we would like to add more feedback into the system. Feedback can be incorporated into the motors, and the seeder. The seeder currently uses a vacuum pump to hold the seed in place while moving to where the seed is deposited. The feedback added would be to monitor the voltage of the pump to detect if the seed is still being held and didn't fall off of the seeder needle nozzle. The motor is currently a stepper motor, but if we need to change the motor we plan on adding an encoder to monitor the position of the motor at all times to detect slippage.

Another thing we will keep in mind while designing the track and tooling systems is the overall appeal of the system. We will try to design a sleek, and attractive track and tooling system to appeal to many customers.

To verify these specifications, we will perform many tests and inspections of various aspects of the designs. For assembly time, we will time the assembly of our new FarmBot drive system. We will perform tests to see the deviation in parallelism our drive system can handle by incrementing the deviation in parallelism and running the drive system until the system cannot handle the deviation. Other specifications, such as total number of parts of the drive system, motor, shipping weight, and shipping size will be verified by inspection. The precision of the system will be verified by testing the system and recording the precision with which the system is able to water, seed, and weed. For the tool head, all of the specifications will be verified by inspection except for cost to consumer and multi-use (water, weeding, seeding). The cost to consumer specification will be verified with analysis of the total cost of the system. The multi-use of the tool head will be verified by testing the functionality of the watering, seeding, (optional soil sensing) and weeding.

Table 1: Track Specs

Spec. #	**Parameter Description**	**Requirement or Target (unit)**	**Tolerance**	**Risk**	**Compliance**
1	Assembly Time	15 hours	1 hour	M	T
2	# of Parts for track system	20% less	minimum	M	I
3	Cost to Consumer	20% less	minimum	M	A, S
4	Precision	Accuracy within 1cm	Max	H	I, T
5	Parallel track	2cm off (of theoretical total distance between tracks)	Minimum	H	I, T
6	Motor	NEMA 17 stepper motor	N/A	L	S
7	Shipping Weight	Reduced by 15%	5%	L	I
8	Shipping Size	Reduced by 10%	5%	L	I

Table 2: Tool Head Specs

Spec. #	**Parameter Description**	**Requirement or Target (unit)**	**Tolerance**	**Risk**	**Compliance**
1	Weight	2 lbs	max	L	I
2	Multi use	Seed, water, weed (optional soil sensor)	N/A	H	T, S
3	Clearance above bed	0.5m (plant height)	5cm	M	I,T
4	Accommodate different sized seeds	(3 sizes, 3 sizes of needles)	Minimum	M	T, I
5	Cost to consumer	20% reduction to tool sub-system	5%	M	A
6	Number of Parts	20% reduction to tool sub-system	5%	M	I

1. Analysis (A)

2. Test (T)

3. Similarity to Existing Designs (S)

4. Inspection (I)

Design Development

We have had many ideas throughout the brainstorming and prototyping process. Most of them we built in the prototype lab where we built 21 model prototypes, 8 for the track drive and 13 for the tooling system (Appendix B).

Here are some of the more reasonable ideas we had:

Tracks

One of the main goals of this project is to either minimize the tracks that the gantry runs on, or get rid of the tracks altogether if possible. The current system uses wheels on a metal track, which is pulled along a timing belt. This track system is very reliable, precise, and efficient. Finding a way for the gantry to run back and forth without being attached to a track proved to be difficult while maintaining any precision.

Four-Wheel Drive

Initially when we thought about completely removing the tracks, the idea was to have the gantry move independently without being connected to the raised planter bed. Our first idea was to have the motors directly power wheels that would roll on top of the raised bed. To make sure there would be enough traction we would power 4 big rubberized wheels, making it four-wheel drive. The idea was simple and in an ideal world could work, but there was no way to keep it on the planter box frame without falling off. Also, if the wheels slipped or ran over a piece of dirt or rock the alignment of the FarmBot in relation to the raised bed would change and it would think that the gantry moved a different distance than it actually did. Without being tied in some way to the ground or planter box, there was no way to know if the gantry was in the correct reference frame or not. This system could be more beneficial in a scenario that does not have a raised bed and FarmBot becomes free range. This idea would need a lot more additional support such as GPS and visual recognition software.

Tank Drive

Taking the whole FarmBot system off the raised bed entirely was another idea that we called the “tank drive”. For this idea, we took away the tracks completely and put caterpillar treads, like those used on some tanks and tractors, and attached them to the bottom of the gantry columns. By not having the gantry on the raised bed, we eliminated the worry of the previous design about staying on top of the raised bed. This idea also comes with a lot of problems, and like the last design with wheels on the top of the planter box, it will also have an accuracy loss from not having a reference to the planter box. There is also more variability on the ground that the FarmBot would be moving on, and extra work added to make it flat and level. As fun as the idea of turning FarmBot into a tank would be, it would make it wildly inaccurate and unpredictable. If this system could be made to be accurate enough it could have applications for more large scale automated farming that does not use planter boxes. Fendt, a European company, recently unveiled a similar idea to this with their small robot tractor called Xaver. This idea uses swarm technology to send many small automated units out into the fields to plant crops.

Timing Belt Without Tracks

The timing belt works well to move FarmBot a certain distance down the planter box, so we thought to keep it but remove the tracks. One of the main benefits of the tracks are that they keep the gantry centered on the planter box. Also, having wheels on top and bottom of the tracks is effective at counteracting any moment on the gantry that would make it fall forward or backwards about its y-axis. To regain control of these degrees of freedom that the tracks gave, a few other adjustments and additions were also designed to make the system work without them.

We had a couple of ideas that involved plates that were parallel to the raised bed that would constrain movement in the y-axis. This would control a parallelism tolerance zone with the walls of the raised bed and be self-correcting when the plates slide against the raised bed. One of these ideas was to use a “flange wheel” that is basically a wheel that has a flat plate or disk attached to one side of it. This flange wheel would be easily added and keep the FarmBot aligned on the planter box. However, we discarded this idea for a solution with a plate that is more fixed. Another idea is to have big wheel plates that can slide against the raised bed as well support the wheels and belt pulleys.

The timing belt will lay flat on top of the planter box frame instead of being protected inside of the track that was removed and attached to each end of the planter box. The belt will be exposed on the planter frame and the flange wheel will be rolling over it, so a channel will be cut into the middle of the wheel so that the wheel won’t crush the belt.

Winch Drive

Another very promising idea that we came up with we called the winch drive (Figure 3). The idea was to find something similar to replace the timing belt but retain the necessary accuracy on the planter boxes reference frame. By using a winch like system that rotates a spool, or driving axle, the motor on the gantry will pull a wire or string that is connected to either side of the planter bed frame and move the gantry. There are two design ideas for the wire: attach two wires to the spool, one going clockwise and the other counterclockwise, or have one wire that is attached to one end, wrapped several times around the spool, and then attached to the other side of the planter box. Using a wire is better than the timing belt in some ways, but not as good in others. The wire is much cheaper and more available than the timing belt, but the timing belt has much more precision and we already know it works.

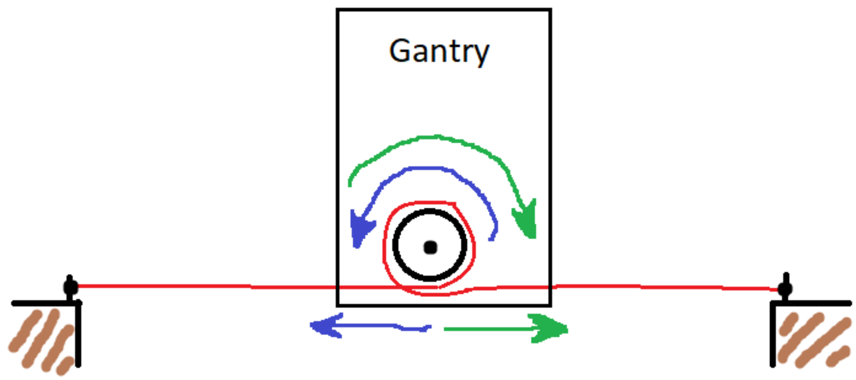


Figure 3: Sketch of the winch drive track system. This shows the motor pulling the gantry with a wire (red) by rotating a shaft to move the gantry left (blue) or right (green).

Tracks Decision

We chose two options to investigate further: the new belt drive, and the winch drive. We wanted to develop both of these designs further because they both had advantages over one another. Looking at the Pugh matrices, we saw that the winch drive seemed to have more benefits and be a better option than the belt drive. After further thought we decided to keep the timing belt system that was used in the original FarmBot because with no slip, making it drives very precise and repeatable. Another benefit of the timing belt option is how the timing belt is integrated into the FarmBot web app that team PLANT3D uses to test the new system.

Tool head

By trying to create a track system that could adjust to deviations in the raised planter bed, we assumed that we would need to design a tool head to combine all of the necessary tools into one package without grabbing them from the tool bay. This assumption was based on an expected loss of precision from not having the gantry guided on a rigid track system.

Turret Head

One of our first ideas was a rotating "turret" tool head, as seen in (Figure 4). It's a really cool looking idea with a wow factor, and our sponsor Rory loved it. Although it's a great idea and could work well, we decided to not use it for a few reasons. First of all, because the tool head needs to rotate, there must be a motor or some mechanism to turn the turret head to different positions. The motor would need to be powered and have extra coding added to make it move correctly, bushings and seals will need to be added to make sure some parts stay dry or move freely. Overall, adding an extra motor would add cost, more assembly time, and more complexity to the system.

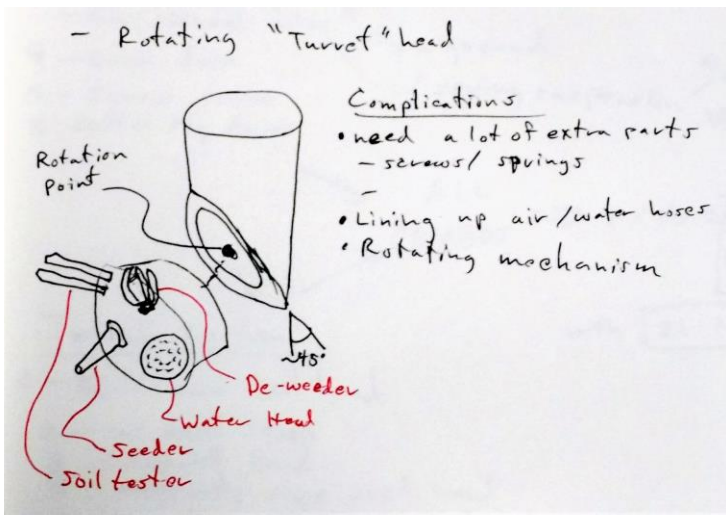


Figure 4: Rotating "Turret" tool head design sketch

Remote Bluetooth Soil Sensor

Another interesting idea was to use a separate soil sensor not attached to the gantry or tool head that could be placed anywhere in the garden and send results of water content via Bluetooth. When designing a multi-tool head this can free up some space for other more important functions than the optional soil sensor, but it also has quite a few drawbacks. One of the benefits of having it attached to the head is that multiple places in the garden can be tested at once, whereas if the sensor is stationary it will only measure water content in one spot. The sensor will also need to be powered, either by battery or hardwired, and rely on a Bluetooth connection that is less reliable than being directly connected. This idea was discarded because it will add more parts and complexity with little added benefit.

All-In-One Tool Head

In the end, we kept coming back to an all-in-one tool head, combining all of the necessary functions into one tool head: planting seeds, watering, weeding, and soil sensor. By only having one tool head instead of having separate attachments for each tool, we can greatly reduce the number of parts used, cost, and assembly time. Some of the parts that were used in each of the individual tool head attachments would only need to be used once in a multi-function tool head. Also, some of the parts wouldn't be needed at all with an all-in-one tool head. For example, the magnets that were used to grab the attachments from the tool bay won't be necessary anymore (18 X $3 = $54 savings).

Decision Process

Once we became familiar with the FarmBot system and established design requirements, we began brainstorming potential solutions and designs. The brainstorming combined with rapid prototyping using foamcore, led to us develop several different design concepts. Once we had designs we felt comfortable with and fulfilled the project requirements we started comparing designs. Using Pugh matrices (Appendix B) to compare different concepts allowed us to better visualize the pros and cons of each design. We began throwing out certain designs that simply were not good enough and did not meet any requirements. When looking at the track replacement concepts we realized we were primarily concerned with two things, movement and stability/linearity. We compared the concepts separately on these two categories using different pugh matrices (Appendix B3 and B4). Doing this lead us to combining different ideas, using what one design did well and replacing another part of it with something from a different design. This is what led to our flange wheel with timing belt design. The design our decision process converged on was the flange wheel, timing belt driven, and all-in-one tool head.

Drive System Prototype

The current system uses tracks for the gantry to run on. This gives the FarmBot its precision, but the tracks are very time consuming and hard to set up and align. The tracks are attached to the raised bed which swells and changes shape if the wood, for example, gets wet. The wheels that run on the tracks are also very sensitive to dirty tracks. The whole gantry will stop if a small piece of dirt gets on the tracks, which is currently a big problem. So by getting rid of the tracks the system's precision will decrease, but it will gain reliability and reduce the cost of FarmBot.

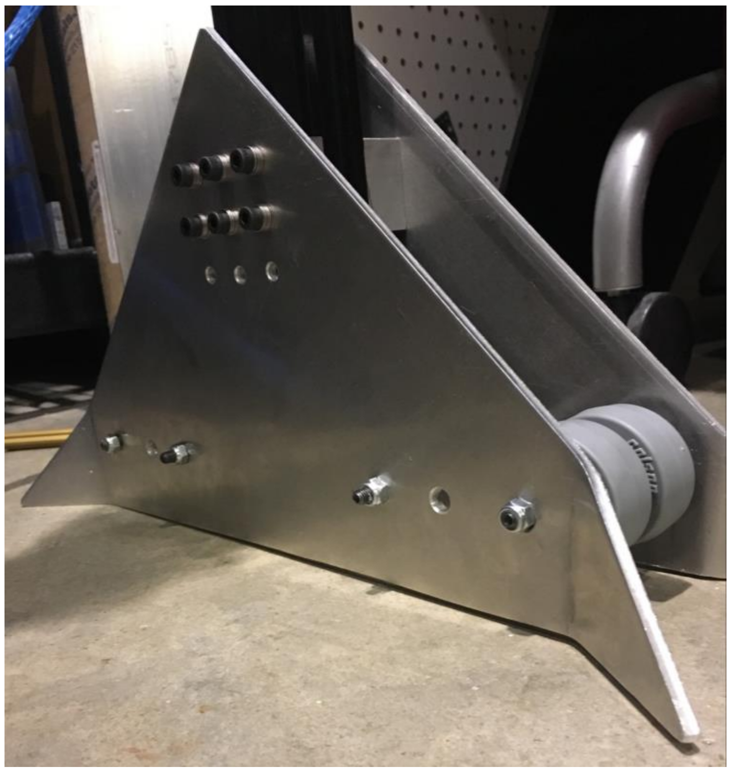


Figure 5: Wheel Plate Prototype 1.

The concept for the tracks is similar to the current system in that it uses a timing belt and a stepper motor, but the wheels run on the raised bed, instead of tracks. The concept is visualized in Figure 5.

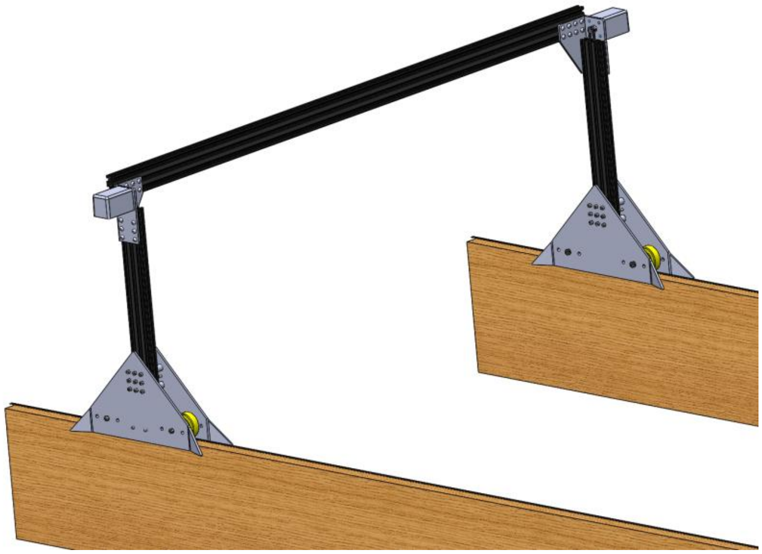


Figure 6: A prototype of the drive system for the gantry.

The concept has one pair of wide wheels on either side of the gantry that run on top of the raised bed. Three different views of the wheels are shown in Figure 6. The left one shows when the wheel is perfectly centered and the gantry is running freely on the bed. The middle and right picture show the wheel plates function, that is to prevent the gantry from falling off the bed. This is also the maximum deviation in the y-direction of the gantry, assuming a perfectly built bed, so by limiting the space between the wheel and the wheel plate the precision of the system can also be limited. For example, if there is a distance of 1 cm between the wheel and wheel plate the allowed tolerance in movement in the y-direction is 1 cm.

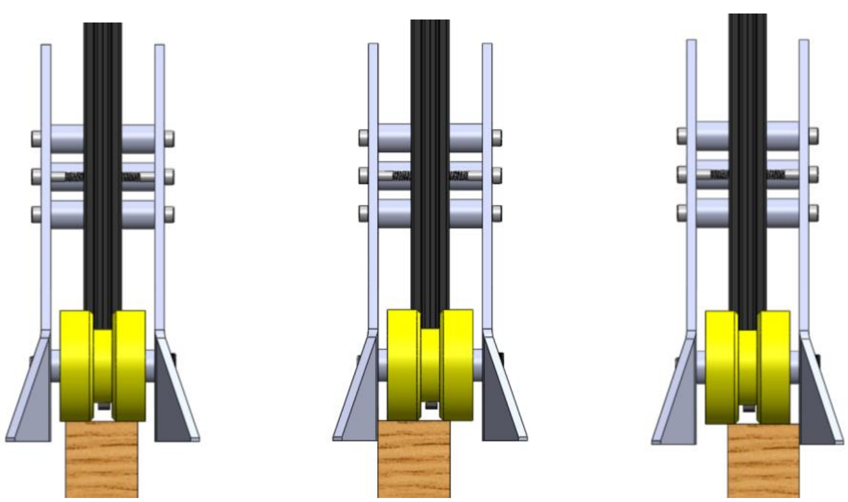


Figure 7: Three different positions of gantry on the raised bed.

The timing belt that drives the gantry will be fixed to both sides of the raised bed and the belt will run through the wheels, thanks to the slot in the wheel shown in Figure 8.

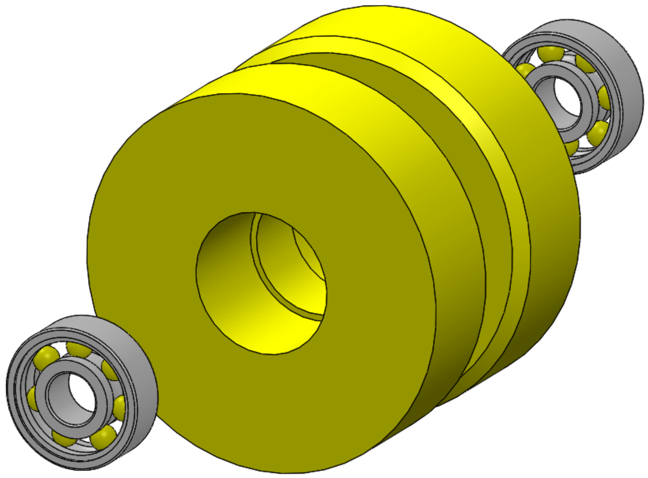


Figure 8: Wheel with a slot and its bearings.

Figure 9 shows the path of the timing belt inside of the wheel plate. After going under the wheels the timing belt is guided by rollers that helps the belt to bend 90 degrees and go into the vertical gantry arm and up to the motor shown in Figure 10. The motor is the NEMA 17 stepper motor, which is what Farmbot currently uses to move in the x, y, and z directions.

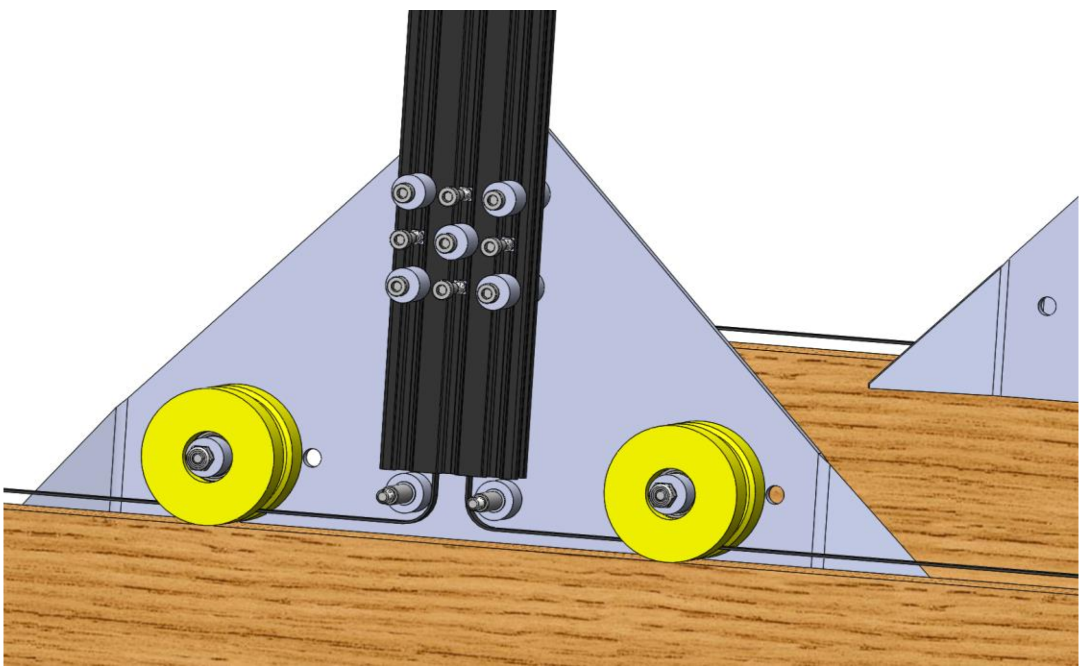


Figure 9: View of belt with one plate detached.

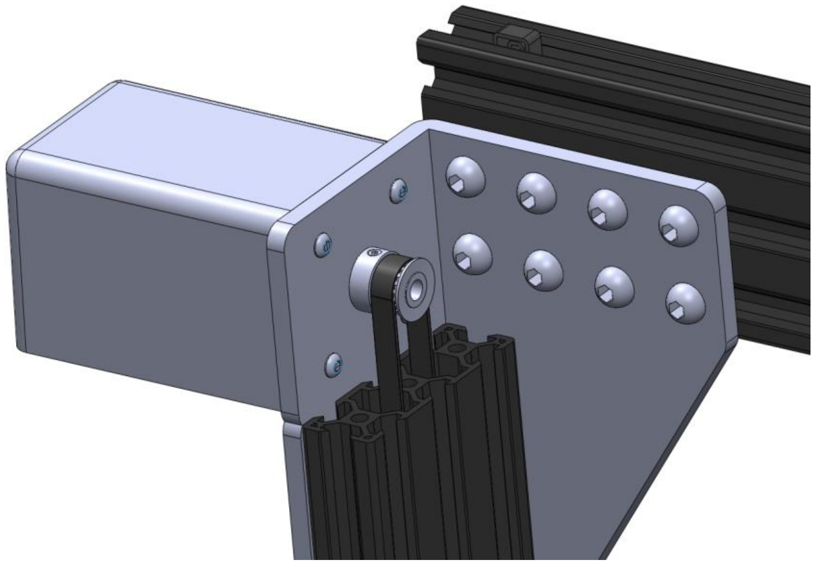


Figure 10: X-axis motor placement on the top of the gantry arm.

Detailed manufacturing drawing and assembly drawing of all the new components in the system are attached in Appendix C.

All-In-One Tool Head Prototype

We decided to design the new tool head as an all-in-one design, bringing together the three required functions: seeding, watering, and weeding, and the optional soil sensor function. The original tool head system uses a “Universal Tool Mount” (or UTM) that can pick up and use many different attachable tools that are stored in the “tool bay”. FarmBot needed the tool head to be fairly accurate in order to take tools in and out of the slots in the tool bay with a tolerance of about ±1 mm. Because the accuracy of the tracking system is expected to be significantly reduced, the UTM will not be able to precisely locate the tools and pick them up from the tool bay any more. By having all of the tooling functions already attached to one tool head, it would only need to be accurate enough to water the plants, giving a tolerance of at least ±1 cm. This will greatly reduce the cost, number of parts, and assembly time.

The seeder function is basically the same as before, using many of the same parts but integrated into the all-in-one tool head. The original idea (Figure 9) is to use a Luer Lock syringe needle to pick up individual seeds with a vacuum created by a small pneumatic pump. This design takes very little room on the tool head, leaving room for other tools. Different sized needles can be attached for bigger or smaller seeds. One of the things we are most worried about is getting dirt shoved in the needle or getting the needle damaged when the tool head gets close to the ground to perform weeding or soil sensing duties. The needle is only used initially for the seeding process and is unnecessary afterwards until the next planting season. Therefore, we can take off the needle and put on a plug to protect it from dirt and the environment when it is not being used.

Figure 11: The original seed injector tool head with a Luer Lock style needle.

The original watering tool head (Figure 11) was made with multiple 3D printed or injection molded plastic parts that are press fitted together. The watering function takes up a lot of space, so there are a few ideas on where to put on the new tool head. Some of the ideas are very similar to the original design where the water goes through the tool head and comes out of an array of small holes to let out an even sprinkle. One of the ideas for the whole array on the all-in-one tool head was to either be a ring of holes on the outer edge with all the other functions in the middle. Integrating the watering function directly into the tool head would be ideal but is more difficult to manufacture. Even when 3D printing the original attachment for watering, it must be made in multiple parts. With the future goal of the all-in-one tool head being made using injection molding, this would prove an even greater challenge and might need an expensive die used to mass produce them.

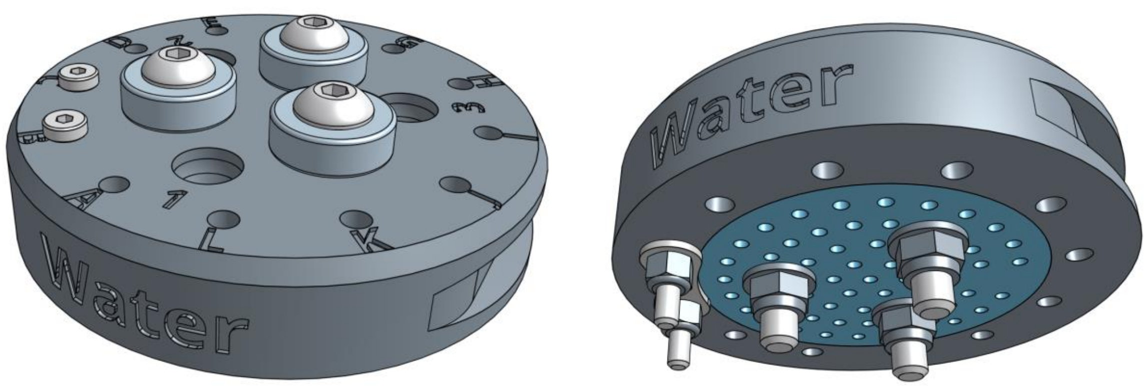


Figure 12: Original watering tool head, top and bottom respectively. The blue piece in the middle of the bottom is a separate piece that is press fit and bolted onto the main tool assembly and contains the holes for the water to come out of.

Another good option for the watering function is to connect a separate sprinkler head, like the one in (Figure 12), onto the tool head instead of trying to integrate it into the plastic.

This approach might not look as slick as having it totally integrated into the tool head, but it is much simpler to make with fewer plastic parts that would need to be 3D printed or injection molded. Both of these processes would cost more and would need a way to be fastened together. The watering nozzle would most likely be made from brass or a similar metal that is corrosion resistant, cheap, and easy to work with. The nozzle will only take up as much space as the connection point instead of taking up half of the space on the tool head.

Figure 13 shows two different spray nozzles with similar spray pattern. The right nozzle is an anti-clog nozzle and is very convenient in our concept since we are looking into use the nozzle as a weeder as well.

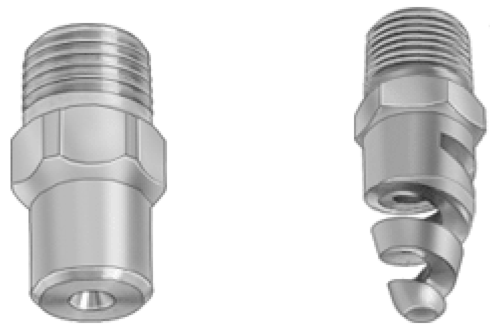


Figure 13: Two possible watering nozzles. Fine-spray cone nozzle and the anti-clog spiral nozzle.

An advantage to having a nozzle that is threaded on, is that the customer can easily buy another nozzle and attach to the tool head. The threads are standard to make it easy to buy your own nozzle depending on what you want to use it on. For example, a light misting spray nozzle can be used to grow mushrooms which requires a more humid atmosphere that the mist provides.

The weeding function of the all-in-one tool head will be much like the original version, where it will smash and stab at the sprouting weeds with spikes and blades until they are destroyed (Figure 14). The idea behind this weeder is that it works when the weeds just start to come out of the ground and not when they are full grown. When weeds or anything that is not growing where it is supposed to start to sprout at the surface of the soil, the camera sees the green pixels that are not supposed to be there and will recognize them as a weed. Then the weeder spikes and blades will push it back under the ground and disrupt the fragile, newly forming root structure enough to kill the weed. This concept has already proved successful on previous designs, so we know that it will work for our new design. This idea is a proactive approach and assumes that the garden initially starts without weeds growing in it. The weeder will not work on big mature weeds that have a stable root structure, and these will need to be removed when FarmBot is set up.

Figure 14: Original weeder tool head attachment. This shows both the weeder spikes and the weeder blades, two options that can be added or removed as desired.

The soil sensor was considered an optional requirement, but we were able to incorporate it into our design of the new all-in-one tool head. Since the shape of the soil sensor is not much different than the weeder blades, we decided to add the sensor’s prongs for more weeding power. There are a couple things we are worried about with this design. One of them is the durability of the soil sensor prongs, which are part of a PCB that is normally made out of fiberglass. There would be more frequent and heavy use of the soil sensor; it might accumulate wear or get damaged over time. In the future we will run tests on the sensor to find out how sturdy it is.

Seed Holder

By removing the tool bays from the FarmBot design, we are also removing the current seed bay location. Our idea is to integrate a seed bay onto the side of the gantry. This will allow FarmBot to always know exactly where the seeds are located relative to the tool head. It will also reduce the total seeding time as the FarmBot will not need to move along the x axis in order to get each seed. This system will allow us to use all of the same parts and functions of the existing FarmBot seeding system without losing any functionality.

Tool Head Overview

Overall the new design for the all-in-one tool head (Figure 15) will greatly reduce cost, the number of parts, and assembly time. It will also simplify the FarmBot during the assembly process as well as programming.

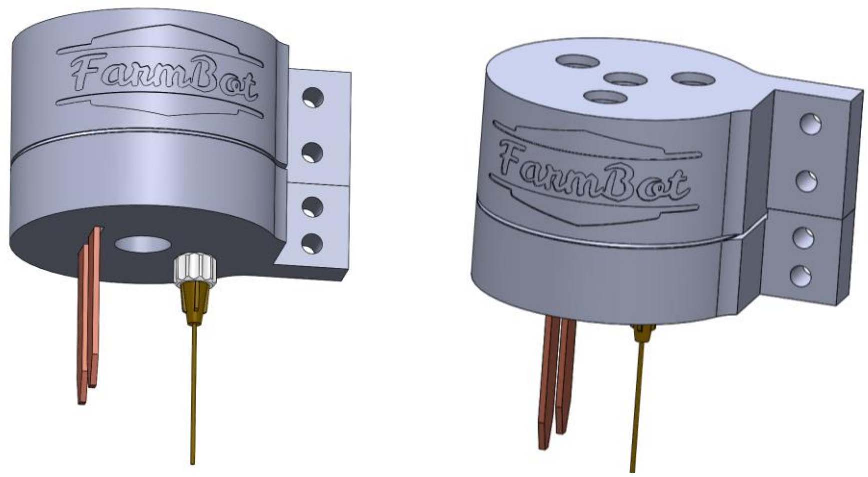


Figure 15: All-in-one tool head concept with combined weeding and soil sensor without the spray nozzle attached.

The current design has two parts, an upper cover and a lower. The lower part is where all the different tool heads are attached to and the upper is just a cover with a logo and holes for the water and air hose.

The new design of the tool head is based on the current design for several reasons. All tool head parts are injection molded and have a high production cost if they are not produced in big numbers. Therefore, we chose to keep the cover and redesign the lower part. Instead of having the universal tool mount (UTM), we are now placing all functions into the lower part as shown in Figure 16. The large hexagon connector in the middle of the tool head (Figure 16) is a standard plastic barbed tube fitting, which allows a nozzle to be inserted from the bottom of the tool head.

The connecting hoses for air and water are not very flexible, so the holes in the upper cover are precisely aligned with the attachments for the seeder and nozzle in the lower part. The electrical cords to the soil sensor can be easily maneuvered to any of the holes in the cover, so that does not need to be considered when placing the soil sensor.

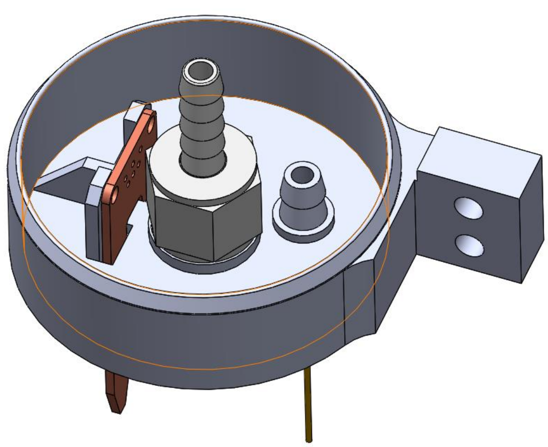


Figure 16: All-in-one tool head with barbed tube connectors.

Programming will be much simpler than the original design that had multiple attachments to pick up. In the original design, the FarmBot needs to be programmed and told exactly where each tool is in the tool bay according to the planter's reference frame. In order to calibrate the system, the user needs to manually move the FarmBot to be right above each tool with a tolerance of a millimeter or so and input the x and y coordinates. The z coordinate has a feedback system where each tool, when connected, will ground out two metal probes that are on the universal tool mount. This is a very tedious and time-consuming process to do for all 4 tools, as well as the seed holder, that can take an hour or two depending on the user's computer skills.

Our final design for the all-in-one tool head is fully developed but has many design options to be finalized later. Most of these options are concerned with where to put the different functions needed onto the tool head. For the seeder, we want to put it as close to the edge as we can, which is closest to where the seed holder will be attached on the gantry. We want the seed holder to be out of the way as much as possible so that Farmbot can reach closer to the edge of the planter, but also be accessible to the seeder needle. The watering function location will depend on whether it is integrated into the tool head or an attachable nozzle. The important thing is to make sure that the water doesn't get to other parts of the system, especially the electrical components.

So far 3 prototypes have been 3D printed and evaluated. The third prototype is the one in Figure 16. This is a functional model but has some disadvantages when it comes to assembly. The holes for mounting the soil sensor are very low and close to the wall, so it takes a long time to assemble which is not ideal.

Material/Component Selection

Current Farmbot supplies and materials were used whenever possible, see Appendix D for details.

Track

For the wheel plates we used the same 6061 5mm aluminum as the rest of the FarmBot bracket and plate hardware. This will allow FarmBot to use the same manufacturer for all of the plates saving costs on mass manufacturing. 6061 is a cheap and effective material that is lightweight and strong enough for our application.

We are using standard hardware (shoulder-bolts, nuts, washers) from McMaster Carr. This is where FarmBot currently orders many of their parts and we want to keep using them as a source for as much of the hardware as possible.

The spacers are made of the same 6061 aluminum as the other parts although it is much thicker. This is a lightweight easy to manufacture material that will be able to be precisely made to fit exactly into our track assembly.

Tool head

The main tool head body is currently 3D printed. We are designing it to be injection molded eventually to match FarmBot's current standard of injection molded tool heads.

Our water nozzle is a standard McMaster Carr part. It will function well as both a weeder and watering nozzle. It is an anti-clogging design which will be important as it will be stuck into the soil in order to smash weeds.

Our design uses the same SparkFun soil sensor as the current soil sensor tool head. This soil sensor works reliably and is heavy duty enough to endure repeated pressing into the soil.

We are using a slightly different size Luer Lock adapter than the current FarmBot system. This new size fits into our tool head better but is ordered from the same vendor and is roughly the same price per unit.

We are using a ¼ inch to threaded hose adapter for the watering nozzle. This is easier than the current system of injection molding a separate nozzle spout like the current FarmBot system. This part will also be purchased through Mcmaster Carr and replaces a comparable ¼ inch barb attachment in the old design.

All of the hardware in this design will be purchased through Mcmaster Carr just like the track system and the current FarmBot system. All of the hardware used in this subsystem is also used in other parts of the FarmBot system which we are not changing.

Final Design Description

The final design consists of the all-in-one tool head, rubber wheels with ball bearings, a timing belt drive system, custom designed wheel plates, with end stops and adjustable belt clips to tension the timing belt with ease. The wheels run along the raised bed with the timing belt running through the adjustable belt clips that are attached to the raised bed with wood screws. Figure 17 below depicts the system which is placed on the raised bed. The x-axis is driven with NEMA 17 stepper motors that have a 14-tooth pulley to adjust the torque of the system.

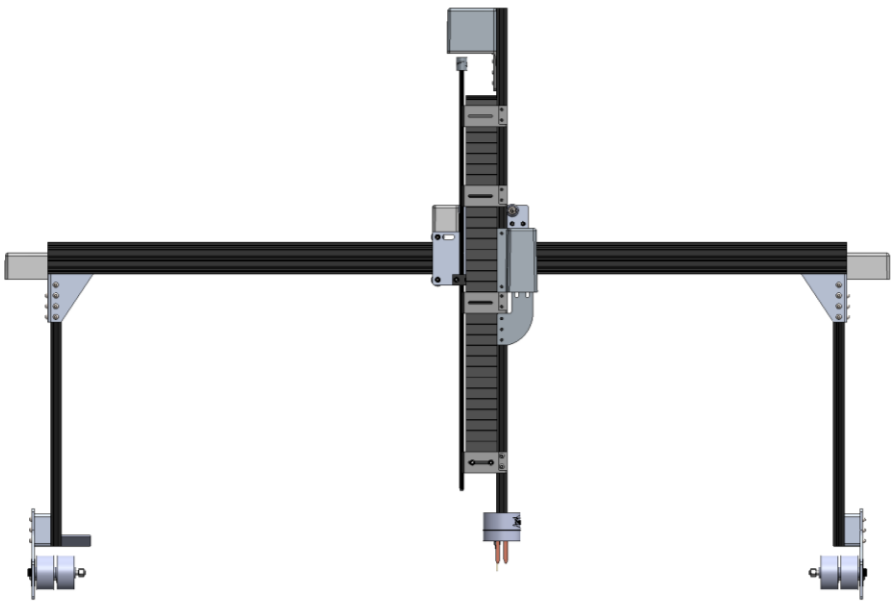


Figure 17: Final design of gantry (Front view)

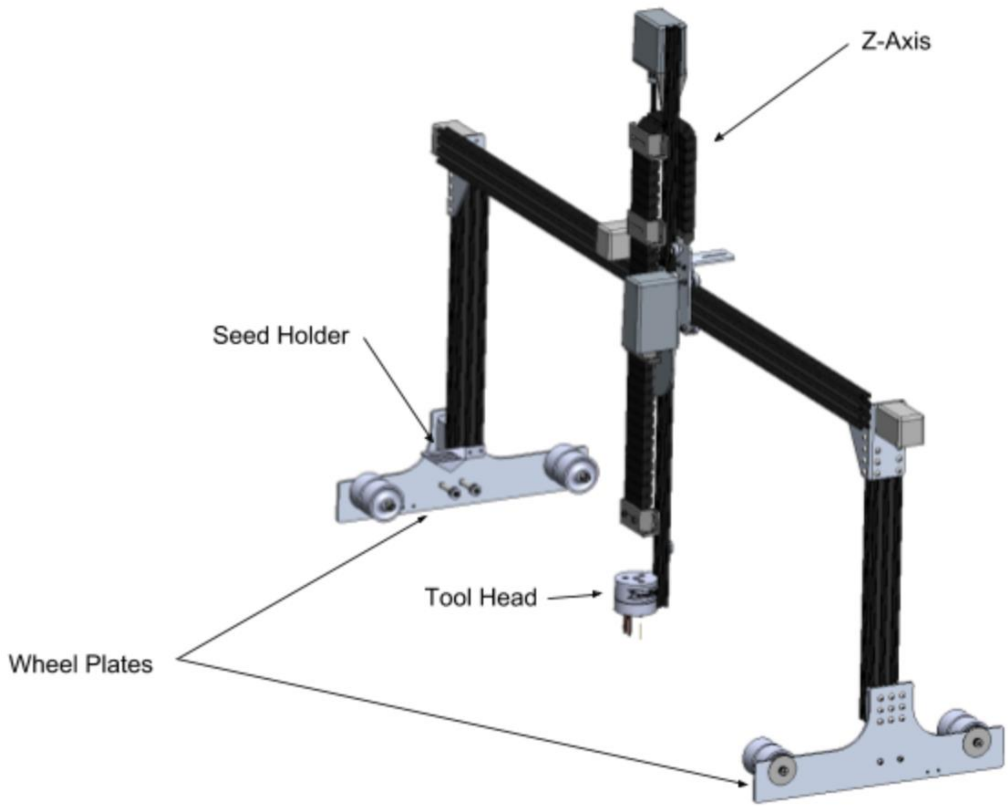


Figure 18: Final design of gantry (Isometric view)

Drive System

Wheel Plate

The components of the wheel plate design are stated in Figure 19, which all are standard parts except the aluminum base plate. The design has 2 sets of parallel wheels on each plate to accommodate for a poorly built raised bed.

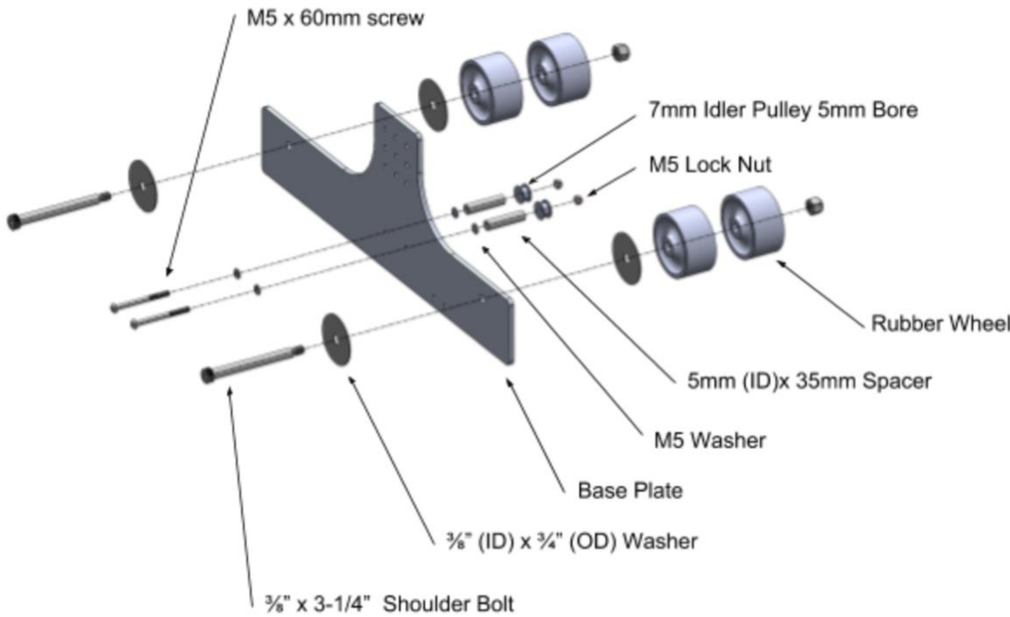


Figure 19: Wheel Plate assembly with labeled parts.

The base plate is a part that is manufactured and is not symmetric (Figure 20), since the weight of Z-axis makes the gantry less stable in one direction then the other. By testing different wheel base dimensions, we could determine a wheel base that gave a stable gantry while still maximizing planting area. The two holes on the bottom of the plate accommodates the X-axis cable carrier to be mounted to the wheel plate.

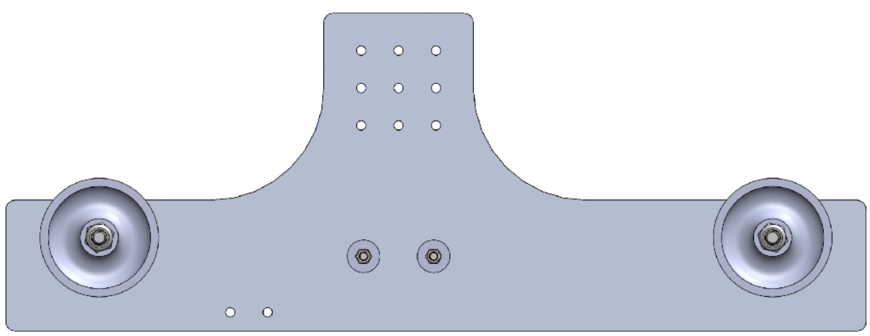


Figure 20: Base plate

The timing belt that moves the system is fastened on each side of the wooden raised bed and runs in between the two wheels and is guided up through the gantry to the stepper motor by idler pulleys. Since the designed wheel plate increases the overall friction in the system the motors that drives the FarmBot along the raised bed were not powerful enough, so the solution was to gear down the motors, that currently has a 20 teeth pulley, to a 14 teeth pulley which is increasing the torque by 30% $\left(\frac{(20-14)}{20} * 100 = 30\%\right)$.

Belt Clips

Since the final design has wheels that run on the raised bed instead of tracks, the timing belt tensioners could not easily be adjusted. The original design fastens the belt clips on the tracks where it easily can be adjusted by just loosen a screw and slide it in the track to adjust the belt tension. The solution was to make a belt clip with a slot (Figure 21) instead of the original FarmBot belt clip that just had a hole (Figure 22). This allows the belt to be tensioned while the adjustable belt clip is still screwed on to the wooden raised bed without making more holes in the wood every time an adjustment is made.

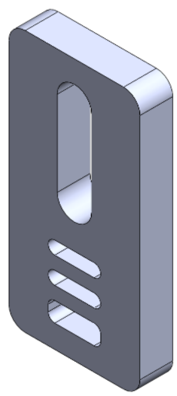


Figure 21: Adjustable Belt Clip

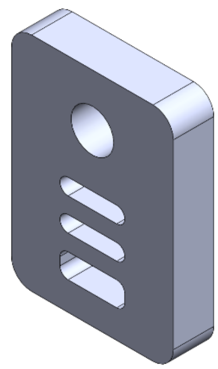


Figure 22: Original Belt Clip

End stops

Figure 23 shows the end stop which is an aluminum plate that is screwed on to the end of the raised bed to stop the wheels from running over the edge. This is mainly a solution to a safety hazard to prevent misuse and avoid damaging the FarmBot gantry. However, this piece should be mounted as low as possible to prevent being a tripping hazard.

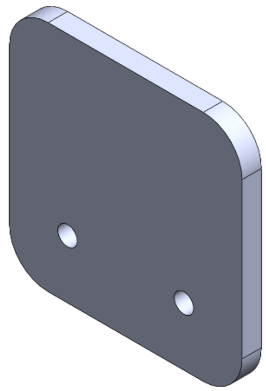


Figure 23: End Stop

Tool Head

The final design of the tool head is seen in Figure 24. The top cover, Luer Lock needle and the soil sensor are the same parts as FarmBot currently using while the changes are the tool base and the water nozzle, which is added to make the water function fit into the size of an old tool heads. By restricting us to the size of an old tool head, we could keep the injection molded top cover in the design. This is saving money since the injection molding tool of the top cover already is purchased.

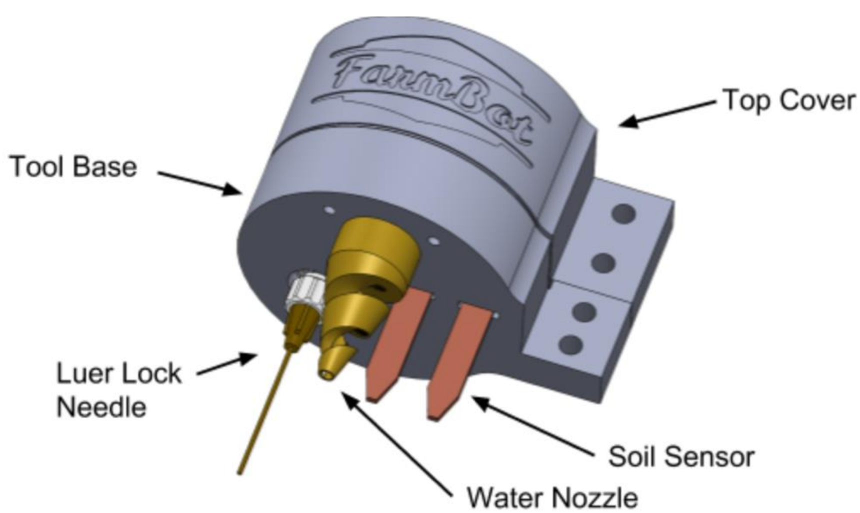


Figure 24: All-In-One Tool Head with parts labeled.

To fit the Luer Lock needle and the water nozzle to the ¼" tubes used for air and water supply, that is currently used in the FarmBot, we connected them with a standard ¼" barbed tube fitting from the inside of the tool head which is illustrated with an exploded view in Figure 25.

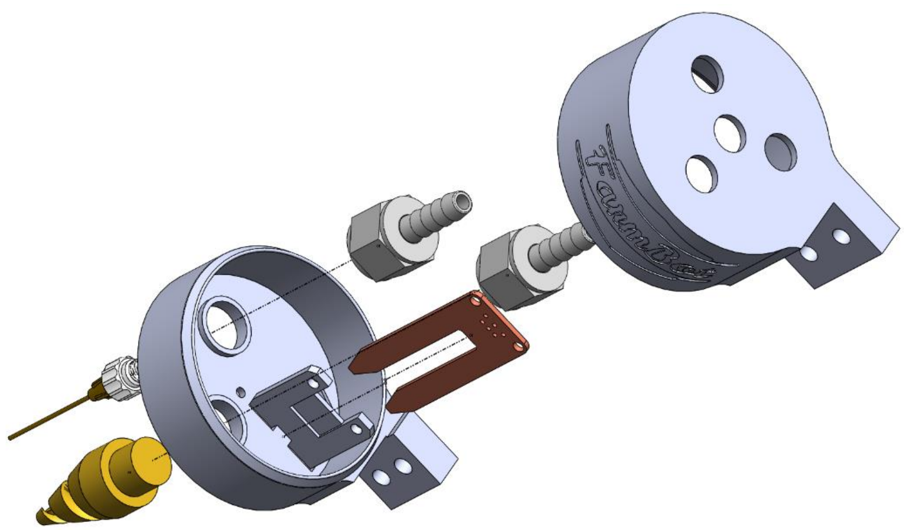


Figure 25: Exploded view of Tool Head.

Seed Holder

The new design loses some of the precision that the original FarmBot has so the seeds would be hard to precisely locate and pick up if they still were in the located in the tool bay, so we created the seed holder seen in Figure 26. The seed holder is located on of the gantry arms and can accommodate for 3 different kind of seeds at the time.

By placing it on the gantry arm, the FarmBot must move along the Y-axis, which has the same precision as before. This is also a more efficient way for seeding compared to the original design because the seed holder always is on the gantry arm, so only movement along the Y and Z-axis is needed while the original design requires movement along all axis to pick up a seed.

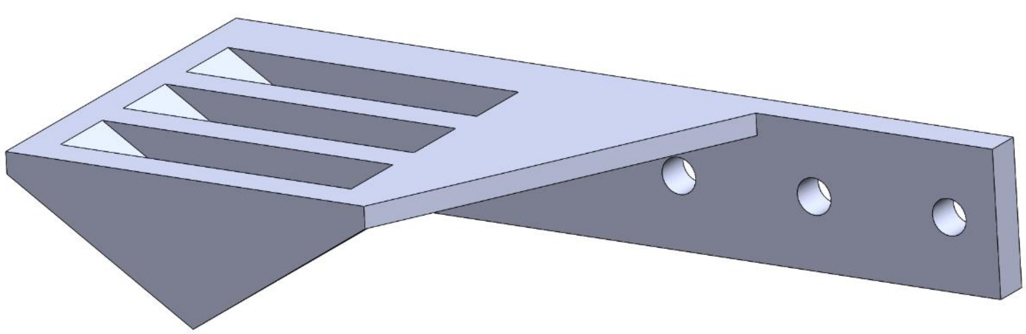


Figure 26: Seed Holder

Cost Breakdown

Table 3: Cost estimates

	Cost of Current Design	Cost of PLANT3D Design	Reduction (%)
Wheel Plates	$253.40	$157.46	37.9%
Other Gantry Parts	$340.20	$338.20	0.6%
Track Parts	$407.85	$224.75	44.9%
Tool head	$235.75	$95.65	59.4%
Total	$1,237.20	$816.06	34%

These costs are made off of the BOM for FarmBot 1.3 (Appendix D) and the prices of off-the-shelf components we used (Appendix E). The cost to the consumer of PLANT3D's design is reduced by 34% in regard to the subsystems of FarmBot modified (Table 3). By removing the track extrusions, connecting plates, magnets, and tool bays over 400 dollars is saved.

System Programming Flowchart

Team PLANT3D utilized the FarmBot web application to create test sequences for testing the all-in-one tool head and the new drive system. The creation of the test sequences was made following the process illustrated in Figure 17.

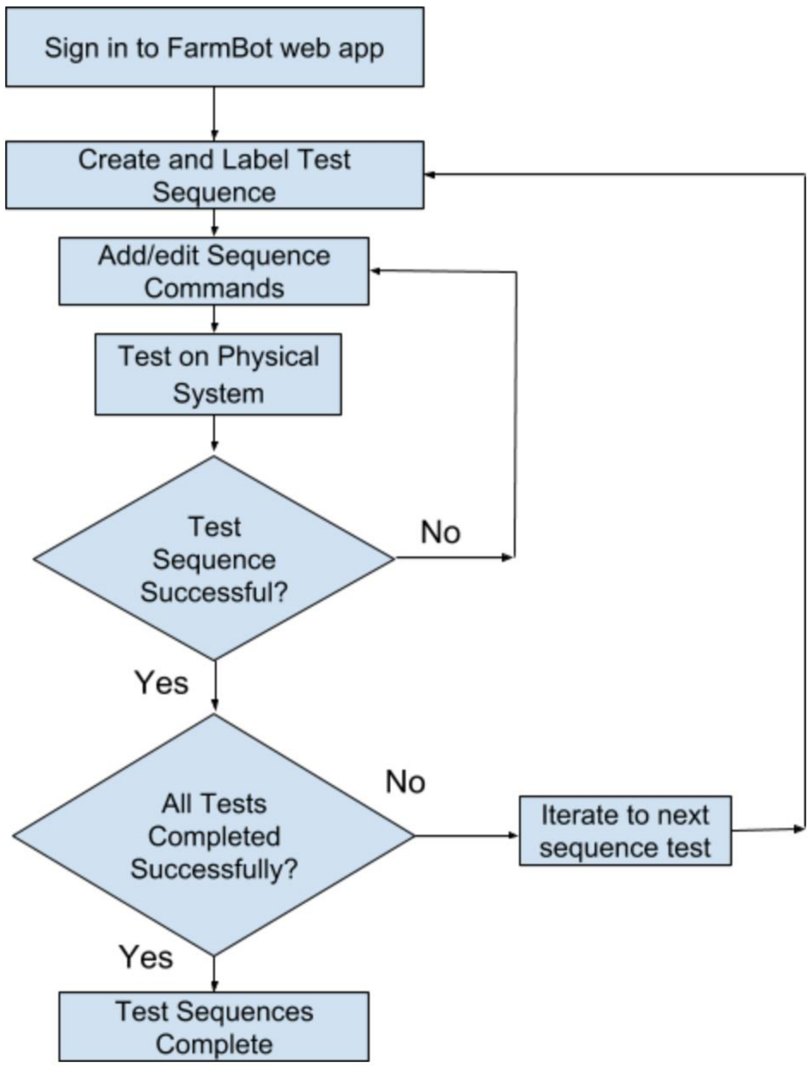


Figure 27: Web Application Flowchart

Safety

To prevent the system from degrading quickly over time, all materials used should be relatively climate and weather resistant. Plastics used should be UV resistant. All materials chosen will be inspected to see if they can last within diverse temperatures, such as 105℉ to -30℉. Making the materials weather resistant will prevent the system from corroding or degrading unexpectedly and hurting a customer.

FarmBot is used as an educational tool to teach children about ecosystems, robotics, and sustainability. Thus, while redesigning the drive system we will try to keep trip hazards low and make the system robust.

Manufacturing

The drive system is mostly made of off-the-shelf components however the wheel plates are machined out of aluminum plate stock. The 5mm aluminum rectangular stock is cut to the shape shown in Figure 28.

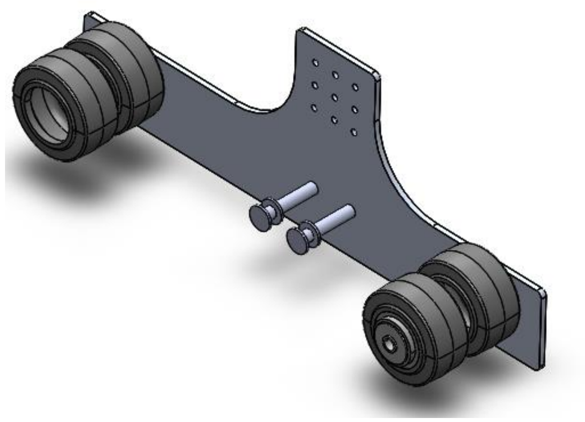


Figure 28: Wheel Plate Rendering

The optical trace plasma cutter (Figure 29) was used to cut the wheel plates to shape. Alternatively, they could have been waterjet cut, but the line for Cal Poly's Industrial Technology waterjet was too long. The holes were made using metric and fractional drill bits on a mill in Mustang 60 and the Hangar. All of the holes are deburred using a deburring tool following the drilling process.

Table 4: Wheel Plates Manufacturing Process

Procure Materials	5mm aluminum plate
Cut to Rough Size	N/A
Operation	Plasma Cut with Optical Tracer following part drawing
	Cut holes with the mill for precision
	Use belt sander to deburr and round corners
	Deburr holes with deburring tool

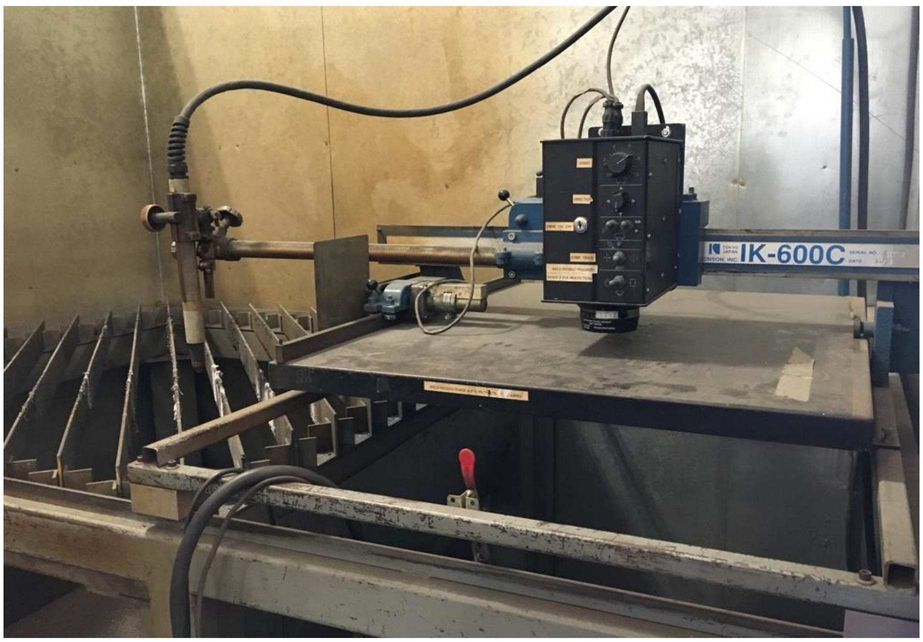


Figure 29: Optical Tracer Plasma Cutter

The block spacers are 3D printed, using the Innovation Sandbox’s Ultimaker 3D printers, to reduce the weight added to the overall system. The all-in-one tool head, and seed holder were 3D printed with the SLO Makerspace’s 3D printer.

Table 5: All-In-One Tool Head Manufacturing Process

Design	Design part and convert to stl file
Operation	Send file to Innovation Sandbox to 3D print

Team PLANT3D designed and manufactured new adjustable belt clips as well. The belt clips were made out of 5mm aluminum plate stock. Then the micro-mill (Figure 19) was used to face the sides of the stock to obtain a better finish. The slots for the timing belt were milled out of the stock with 1/8th 2-flute HSS end mill. The slot for adjusting the tension of the belt was made using a 3/16th 2-flute HSS end mill. The corners of the adjustable belt clips were rounded using the belt sander in Cal Poly's Mustang 60 Machine Shop.

Table 6: Adjustable Belt Clips Manufacturing Process

Procurement	5mm Aluminum Plate
Cut to rough size	Vertical Band saw
Operations:	Face all of the sides of the part on the micro-mill with a 0.25" 2-flute end mill.
	Mill timing belt slots with 1/8" 2-flute end mill
	Mill wood screw slot with 3/16" 2-flute end mill
	Round corners with metal belt sander
	File any harsh burrs

Figure 30: Micro-Mill

The end stops were cut to size on the vertical band saw and then the edges were deburred using the belt sander and a file. The holes were made using a drill press in Cal Poly's Aero Hangar. The holes were deburred with a conical deburring tool.

Pictures of all of the machines used for manufacturing the parts described are found in Appendix J.

Physical differences between Design and Prototype

The design is in metric to follow the convention of the FarmBot system and standardize the tools necessary to make the system. However, there were no metric end mills at our disposal so the PLANT3D team used the closest fractional end mills to the ones mentioned in Appendix C. The end mills used were 1/8th 2-flute HSS end mill to make the slots for the timing belt. The slot to adjust the tightness of the belt was made using a 3/16th 2-flute end mill. The other dimensions of the physical belt clips are also slightly off to accommodate the change in diameter of the slots.

Future Recommendations

PLANT3D designed the all-in-one tool head to be injection moldable. ProtoLabs is a company that specializes in manufacturing injection molded parts. To injection mold the all-in-one tool head it costs approximately $10 per tool head for the consumer. Team PLANT3D also recommends to make the block spacers out of delrin and have them machined, to increase the durability and manufacturing efficiency. The new wheel plate is designed with the intent to be water-jet cut. FarmBot currently uses Big Blue Saw, which can cut the wheel plates from 5mm aluminum plate stock.

Design Verification

Final analysis of our prototype was done in two sections. Overall design verification in the form of analysis and measurement was used to check overall design specifications. Cost and part counts were analyzed by comparing original design specifications and our new prototype design. The other part of testing and verification came in the form of functionality testing. To accomplish functionality testing two different raised beds were used: a new ideal scenario bed which we constructed as a portable testing device and an existing raised bed which was well below the minimum design requirements for a typical FarmBot. These two raised beds allowed us to test the functionality of several different facets of the FarmBot design in both ideal and worst-case scenarios. With the raised bed testing the FarmBot web app was used to write easily repeatable tests to check both normal FarmBot functionality as well as push the FarmBot to see if functionality and precision were significantly impacted by suboptimal sequencing of movements. By testing other movements, we were able to better understand ways in which to improve the system moving forward as well as ways in which to optimize peripheral functions of the FarmBot which we did not directly change in the FarmBot design. Details about each test can be seen below, a summary can be found in Appendix K.

- Assembly Time
  - To figure out the decrease in assembly time of our design two different “unskilled” people assembled the changed subsystems. This involved building the wheel plate assemblies and installing them onto the gantry arms as well as building the tool head and installing it onto the Z axis.
  - The original design takes roughly 195 minutes to assemble on average. This is considerably longer than the 105 minutes it takes to assemble our new design. This is a 46% reduction in assembly time of the tracks and tool head systems, two of the more tedious and difficult systems to assemble.
- # Parts for Tool Head
  - The original part count for number of parts associated with the tool head system and supporting infrastructure is 149 for the tool head. Our new design only requires 22 parts in total. This reduces the part count for the tool head by over 85%.
- # Parts for Tracks
  - For the tracks the part count was reduced from 359 to 153. This was a reduction of over 57%, well over the 20% design requirement.
- Cost to Consumer (Tool head)
  - To test cost to consumer the costs of parts for the new tool head subsystem, all of the costs of both original parts and new parts to the design were compiled, as seen in Appendix D. The cost to the consumer for individual parts, the way FarmBot is currently shipped out, is from $235.75 to $95.65 for a decrease of almost 60%.
- Cost to Consumer (Tracks)
  - The track system saw a smaller decrease by percentage at only 22% but a larger total decrease going from $1,001.45 to $780.41 for the new design.

- Precision
  - To test precision a sequence was built in the FarmBot web app and run for 50 trials with 4 measurements per trial. Measurements were taken at different points around the raised bed to test precision at various points. Each different functional tooling capability was tested to ensure both reliability and precision. Each measurement was taken as a go/no go reading depending on whether the tool head successfully reached within its 2cm target and completed its function correctly. The steps followed in the sequence can be seen in appendix K.
  - After 200 measurements only 7 failed at reaching their targets correctly. Every single function of the tool head was completed fully. All of the 7 fails were due to failures of the z axis moving down into position. The x y positioning of the gantry was correct, or at least within 2cm of the desired location.
- Parallel Track Allowance
  - After testing precision on an optimized bed, the FarmBot was placed on an older, worn out bed. This bed featured large deviations in both sides. The FarmBot was placed on this raised bed to test a much beyond worst case scenario for what type of raised bed someone may want to place a FarmBot.
  - Running the same precision test on this bed showed the maximum deviation which the new FarmBot design could withstand. The FarmBot was still able to run, although with some minor difficulty and at a lower speed, on this raised bed until it reached points with 5cm of outward deviation in each side of the bed. The FarmBot ran smoothly with no pauses over smaller deviations such as the 2cm deviation specification.
- Shipping Weight
  - Shipping weight was calculated by subtracting the total weights of all the parts removed from the parts added to the design. The only substantial change in weight came from the removal of the aluminum extrusion tracks. This led to a decrease of roughly 4kg decrease in system weight or roughly 28%.
- Shipping Size
  - Total packaging size remains relatively unchanged. Due to the main 1.5-meter gantry beam remaining size cannot be largely reduced. Larger wheel plates also reduce the ability to shrink other packaging of the design. Lower total weight will however reduce the total shipping cost. Size could be reduced by splitting the gantry beam into sections and connecting them with brackets as in the FarmBot XL design.
- Multi-Use
  - The functionality testing of the different tool head components was run simultaneously with the precision testing. At no point during the testing did any of the tool head functions fail.
- Clearance
  - Clearance was increased in the overall system from the previous design. The new tool head design is much lower profile that the old universal tool mount design. Without other changes this means that the overall clearance was increased as well.
- Functionality
  - All the timing belts included in the kit were able to withstand forces of over 40 pounds without any noticeable damage.

- Functionality
    - The no clog water nozzle works with the 15 psi pressure regulator that is included in the FarmBot kit. The nozzle also works using a standard house spigot pressure, usually closer to 40 psi.

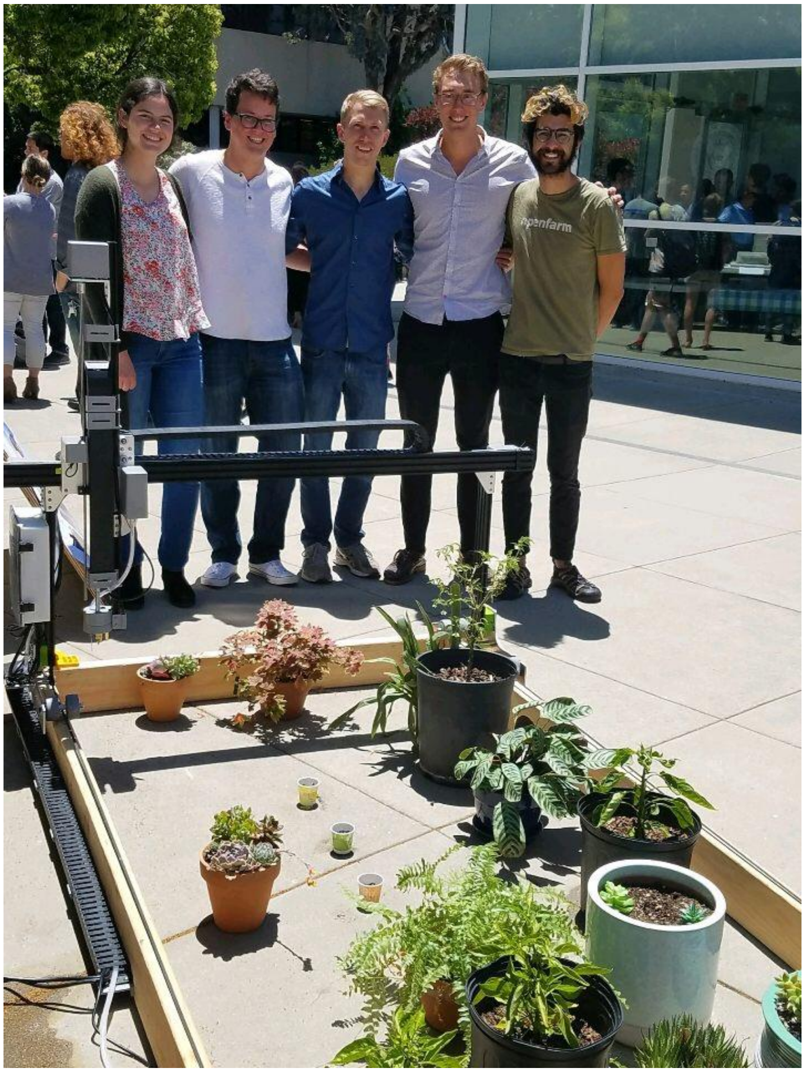
Conclusions and Recommendations

Based on the results of our testing and prototype, we have proved that a FarmBot system is possible without the need for aluminum extrusion tracks. A FarmBot is capable of running directly on the sides of a raised bed without any significant loss in precision. This design greatly reduces the need to constantly check on and adjust the FarmBot between uses due to variations in the raised bed geometry over time. Moving forward with this design allows for an easier setup and opens the possibility of a FarmBot being sold in 3-4 prebuilt main component pieces. This would allow for a potential set up time of just a few hours as opposed to almost 20, reaching a much wider audience of customers than before. There are still several key areas to investigate before moving ahead with this design. Some of the potential areas for improvement and systems to monitor over time are as follows:

- Single wheel plates
    - By using a single wheel plate, a very large moment is produced on the wheel shoulder bolts. This may be enough to cause some deflection in the plates over time causing the entire gantry to sag. If this does happen two potential solutions could be either using thicker wheel plates, increasing the drag while offering more support or adding another plate on the inside of the gantry to support the shoulder bolt on both ends.
- Luer lock needles
    - One of the main downsides to the all-in-one tool head design is that it requires the user to attach and detach the Luer Lock needles from the tool head between every seeding use. If the needles are left in place during normal use they will quickly become clogged during weeding and soil sensing operations. This should not be a large amount of added work for the user as they will already have to load the FarmBot with seeds every time they wish to plant, but it will require that they remember to do so or they will need to swap new needles at a much faster rate than with the current system.
- 14 tooth pulleys
    - The current FarmBot system uses 20 tooth pulleys for x-axis movement. Our design generates much more friction moving along the raised bed. Using 14 tooth pulleys provides enough torque to overcome this force. However, it means there is almost no space between the timing belt and the inner edge of the gantry arm causing potential catches if the pulley is not placed perfectly in the center of the arm.
- 3/8 inch axles
    - Our design uses 3/8 shoulder bolts to work as the axels for the wheels. This goes against the overall metric standard of FarmBot’s design. Moving forward, metric standard wheels would allow the design to better conform with the standard laid out by FarmBot.

Acknowledgments

PLANT3D would like to acknowledge and thank Rory Aronson, the founder and CEO of FarmBot for giving us the opportunity to work on and help develop FarmBot, as well as Karla Carichner for providing excellent guidance and insight. A special thank you to Simon's blue truck for transporting the PLANT3D prototype to and from the project expo, Sarina for the beautiful plants, and Caela for lending a helping hand.



From left: Cailey, Cole, Clayton, Otto and Rory

Appendices

Appendix A: References

Category	# of Components	Subtotal
Extrusions	8	$205.00
Plates and Brackets	24	$367.00
Plastic Parts	56	$267.00
Fasteners and Hardware	810	$189.10
Drivetrain	134	$449.75
Electronics and Wiring	55	$1,039.50
Tubing	23	$88.50
Miscellaneous	121	$95.25
Supporting Infrastructure *	50	$200.00
GRAND TOTAL	**1,281**	**$2,901.10**

Appendix A1: FarmBot 1.4 BOM overview from FarmBot documentation

Appendix B: Decision Analysis

Appendix B1

Decision Matrix: Tool Heads				
	Old System	All-in one	Independent soil-sensor	Turret (rotating) head
Precision	R	-	-	-
Assembly Time	E	+	+	s
Cost	F	+	+	-
# of Parts	E	+	+	s
Maintenance	R	+	+	-
Life Span	E	s	s	-
Reliability	N	s	-	-
Manufacturabilit	C	s	s	-
Functionability	E	s	-	s
Σ+	0	4	4	0
Σ-	0	1	3	6
Σs	0	4	2	3

Pugh matrix of 3 top tool head designs along with the current design as the datum

Appendix B2

	Old Syste m	Belt Drive No Tracks	Winch and Wire Drive	4WD (Not Attached to frame)
Precision	R	-	-	-
Assembly Time	E	+	+	s
Cost	F	+	+	+
# of Parts	E	+	+	s
Maintenance	R	+	+	+
Life Span	E	s	+	+
Reliability	N	+	+	s
Manufacturability	C	s	s	s
Functionability	E	s	s	-
Σ+	0	5	6	3
Σ-	0	1	1	2
Σs	0	3	2	4

Pugh matrix of the top 3 Track replacement designs using the current track system as the datum

Appendix B3

Decision Matrix: Track Drive System				(Movement)
	Belt Drive	Old System	Winch and Wire Drive	4WD (Not Attached to frame)
Precision	R	+	-	-
Assembly Time	E	-	s	-
Cost	F	-	+	s
# of Parts	E	-	s	-
Maintenance	R	-	+	-
Life Span	E	s	s	s
Reliability	N	-	s	s
Manufacturabilit	C	s	s	-
Functionability	E	s	s	s
Σ+	0	1	2	0
Σ-	0	5	1	5
Σs	0	3	6	4

Pugh Matrix of top 3 track systems focusing on movement function

Appendix B4

Decision Matrix: Track Drive System				(Linear Guide)
	Belt Drive	Old System	Winch and Wire Drive	4WD (Not Attached to frame)
Precision	R	+	-	-
Assembly Time	E	-	s	-
Cost	F	s	+	-
# of Parts	E	-	-	-
Maintenance	R	-	+	-
Life Span	E	s	+	s
Reliability	N	-	-	-
Manufacturabilit	C	s	+	-
Functionability	E	+	s	-
Σ+	0	2	4	0
Σ-	0	4	3	8
Σs	0	3	2	1

Decision Matrix: Track Drive System				(Linear Guide)
	Belt Drive	Old System	Winch and Wire Drive	4WD (Not Attached to frame)
Precision	R	+	-	-
Assembly Time	E	-	s	-
Cost	F	s	+	-
# of Parts	E	-	-	-
Maintenance	R	-	+	-
Life Span	E	s	+	s
Reliability	N	-	-	-
Manufacturabilit	C	s	+	-
Functionability	E	+	s	-
Σ+	0	2	4	0
Σ-	0	4	3	8
Σs	0	3	2	1

Pugh Matrix of top 3 track systems focusing on Linear movement and stability.

Appendix B5

Prototype Lab

10/17

Track Drives

① – Belt drive
– Four-Wheel drive
  ② on track
  ③ on ground
  w/ spring suspension
    ⑤ on ground
    ⑩ on track
⑥ – Gear drive
⑦ – Screw drive
⑧ – Butterfly drive

ALL COMBOS ⟹ 8 X 13 = $\boxed{104 \text{ Designs}}$

with $\boxed{21 \text{ Models}}$

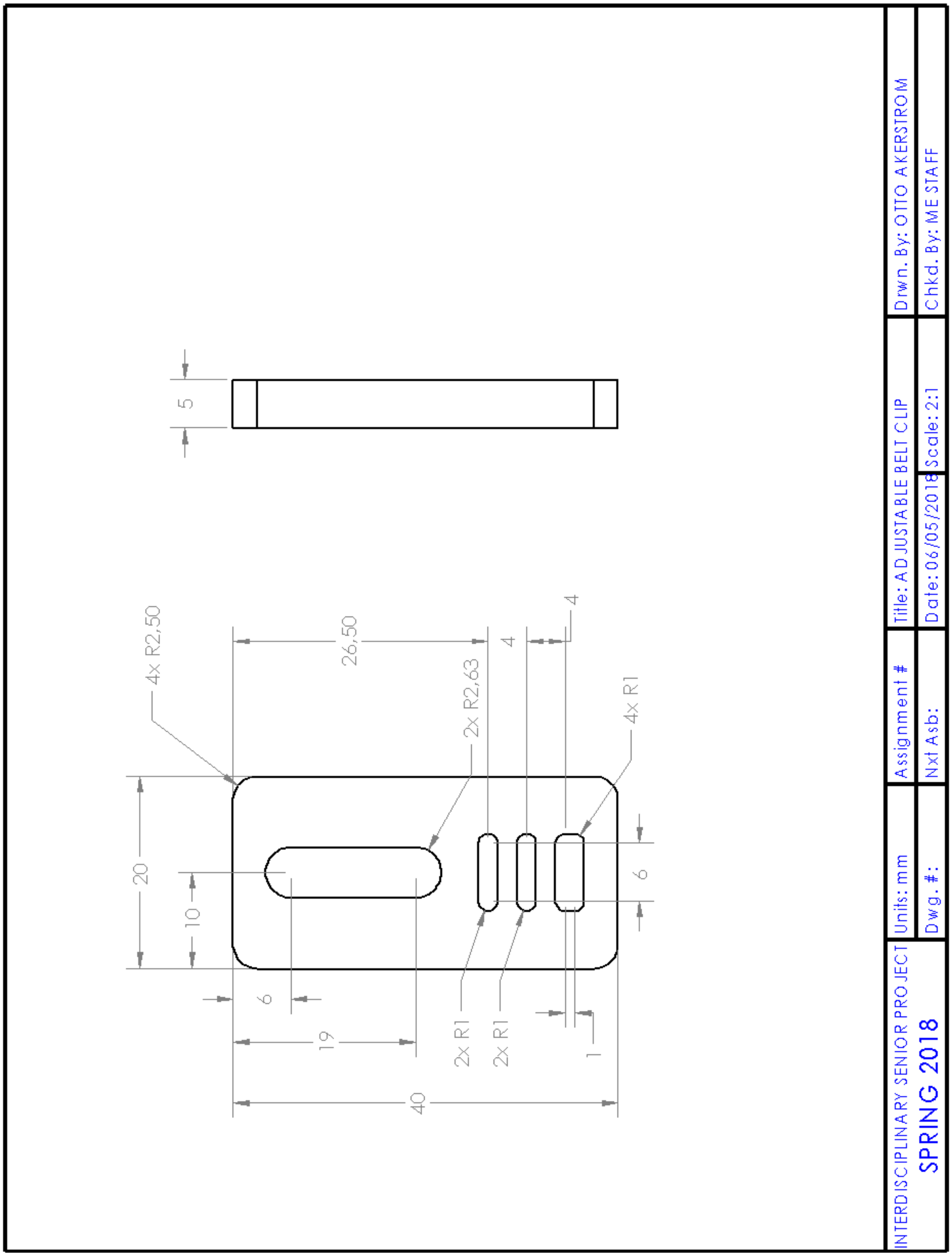
Tooling system

① – All-in-one Tool head
② – w/ seed scoop
③ – Turret Head
④ – alternate size seed head
⑤ – vacuum tube = water tube
⑥ – Heavy duty soil sensor multi-head
⑦ – soil sensor on side
⑧ – round up gun
⑨ – Air gun De-weeder
⑩ – Blue tooth soil sensor
⑪ – laser weed killer
⑫ – Rake extension
⑬ – claw vegetable picker

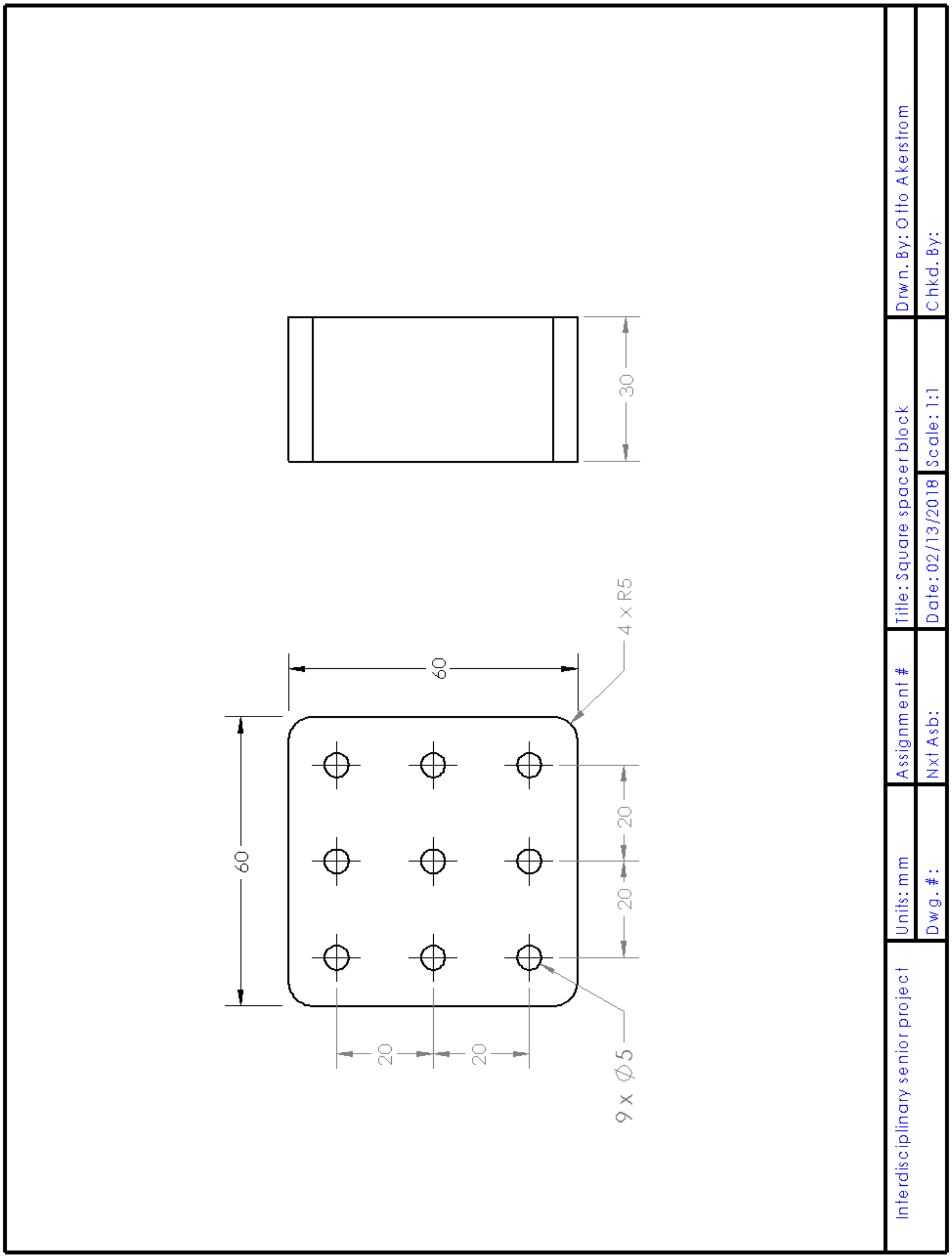
Prototype Lab Ideas

Appendix C: Drawings

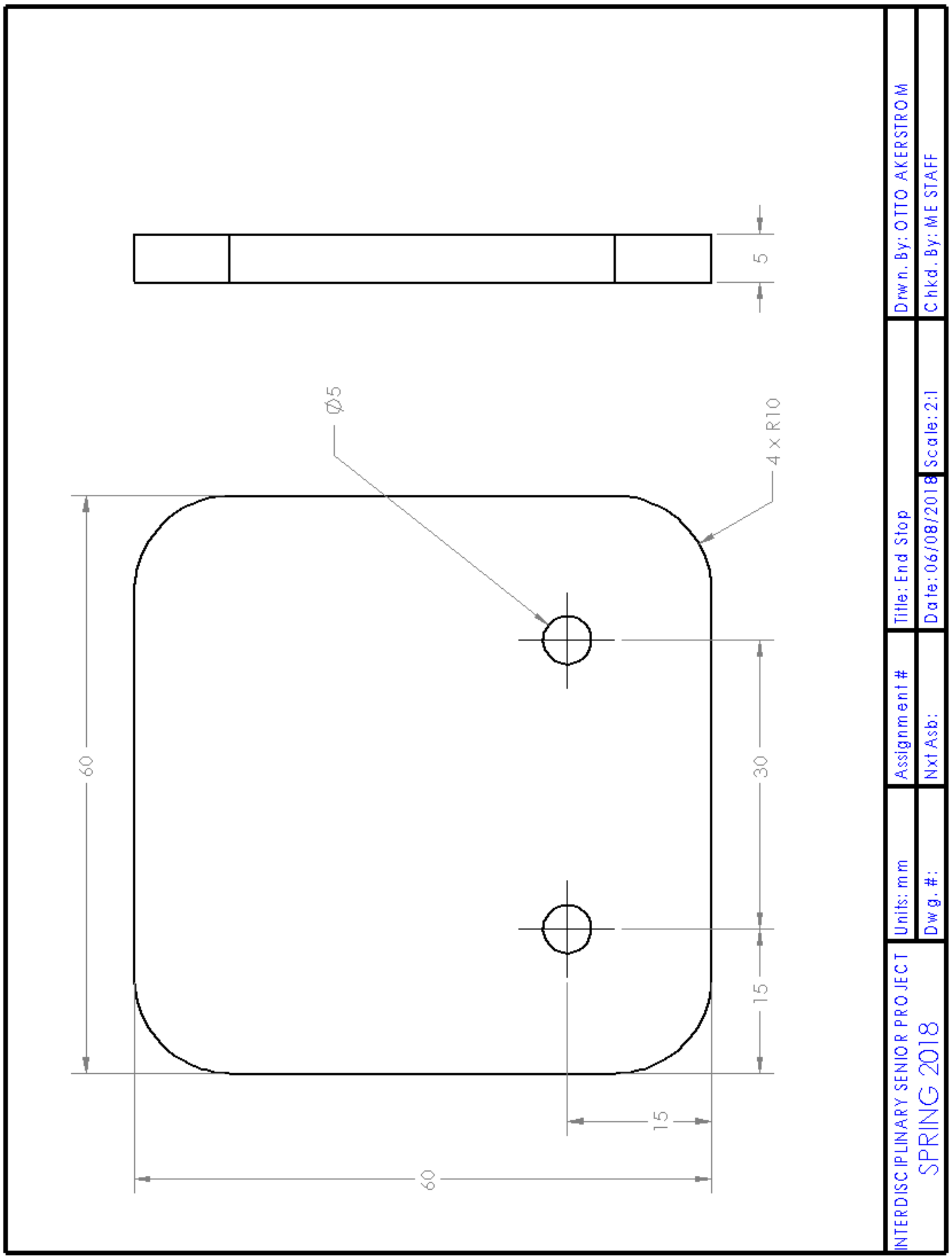
Appendix C1: Adjustable belt clip



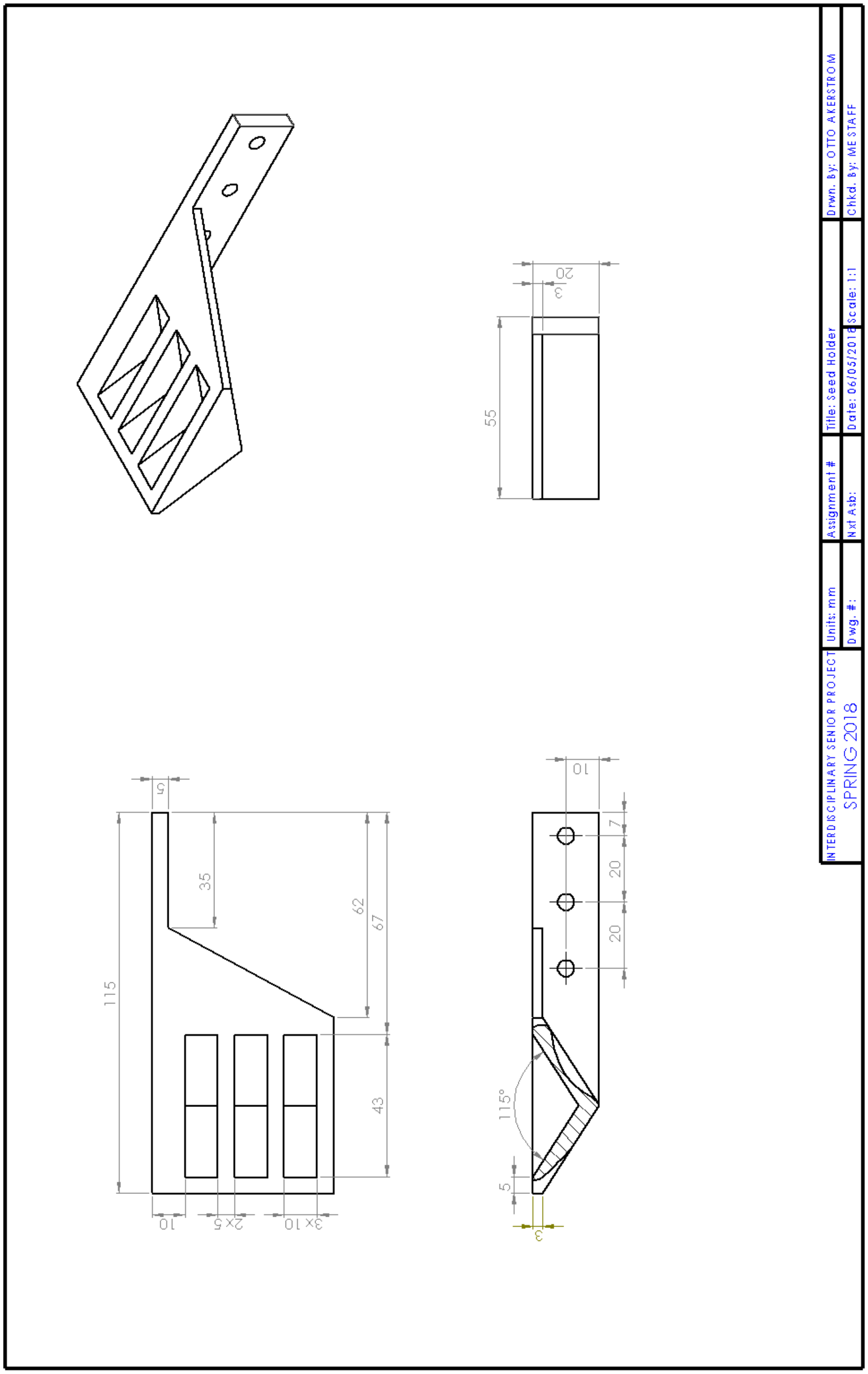
Appendix C2: Block Spacer



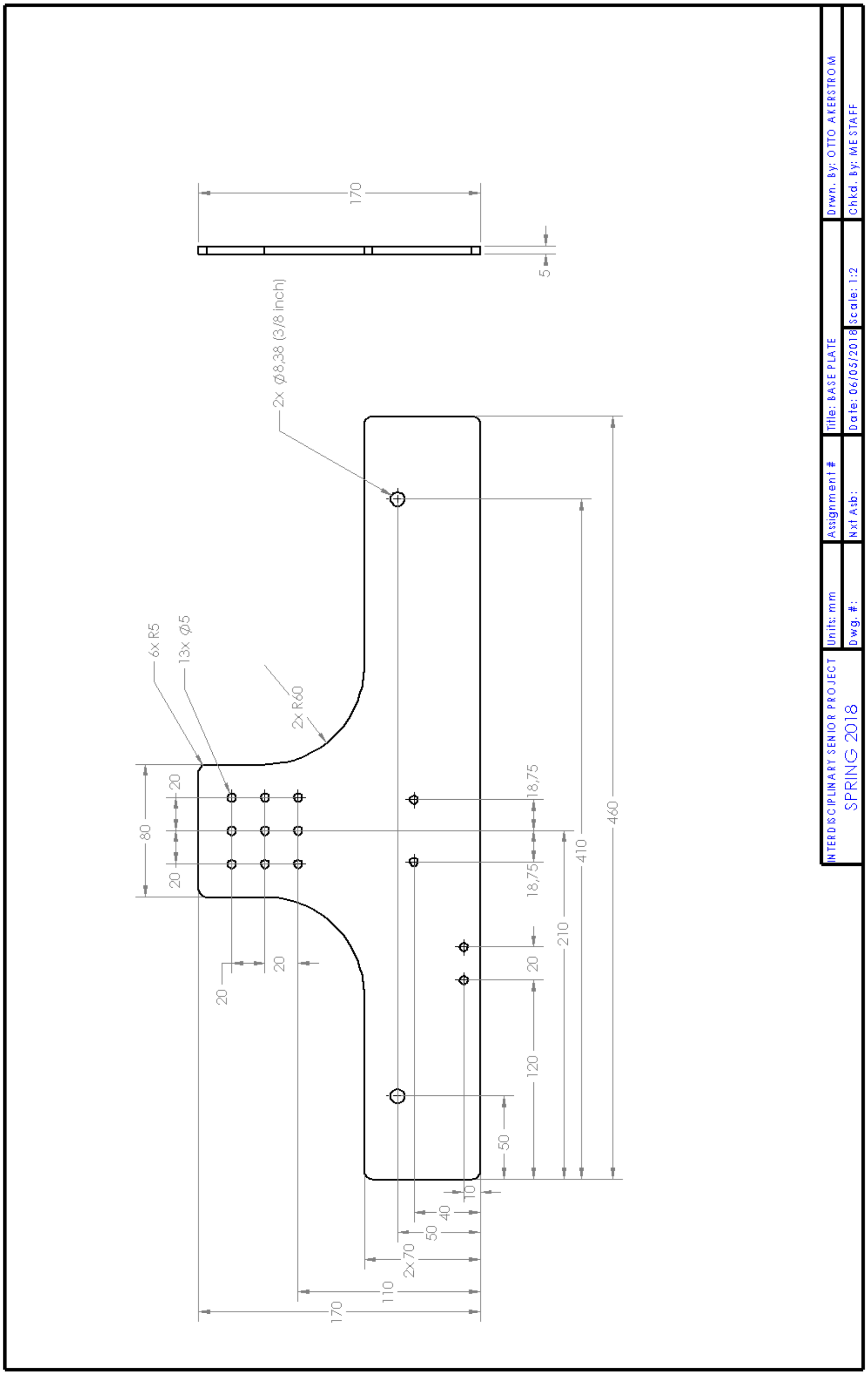
Appendix C3: Skate Wheel End Stop



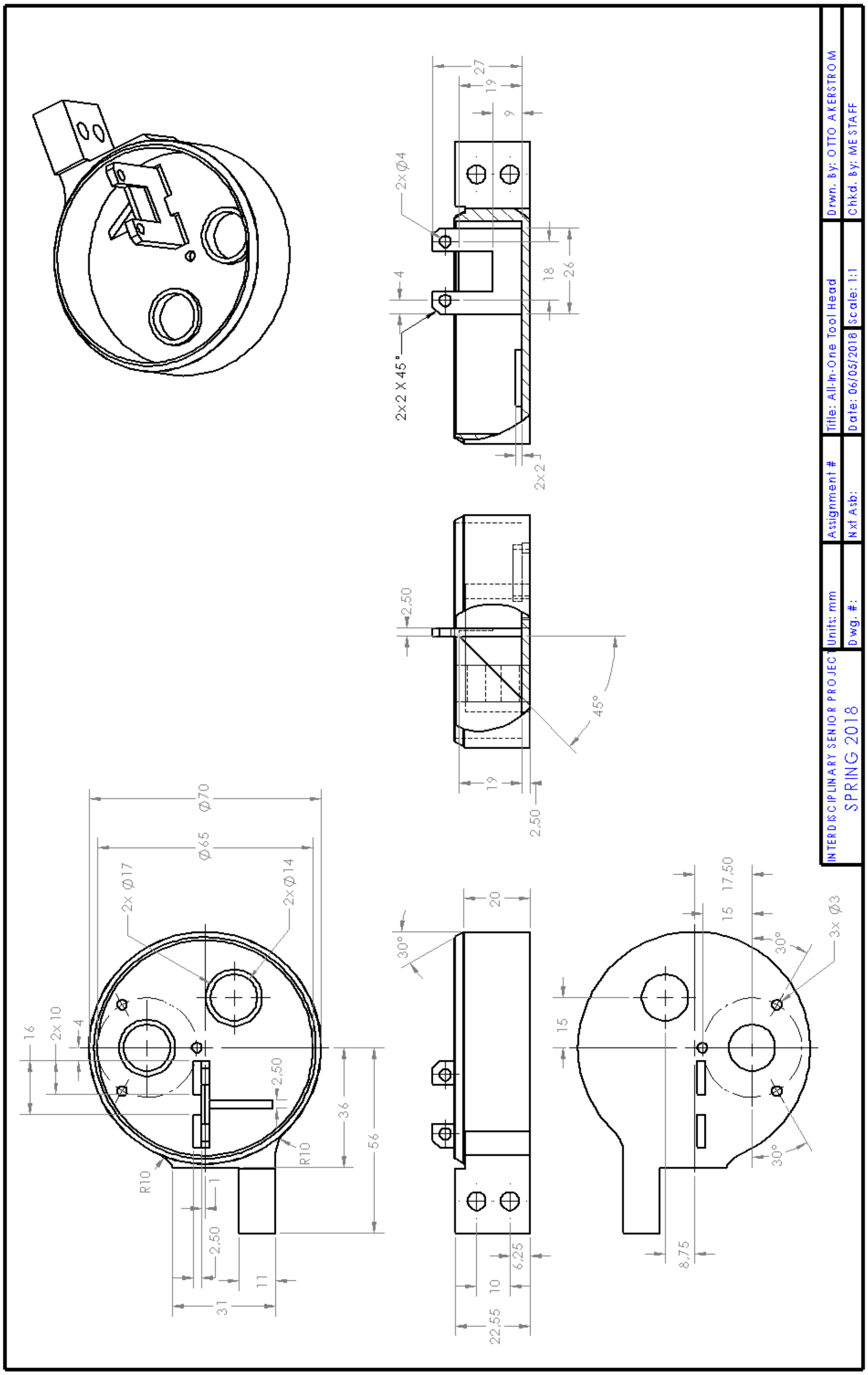
Appendix C4: Skate Wheel Base



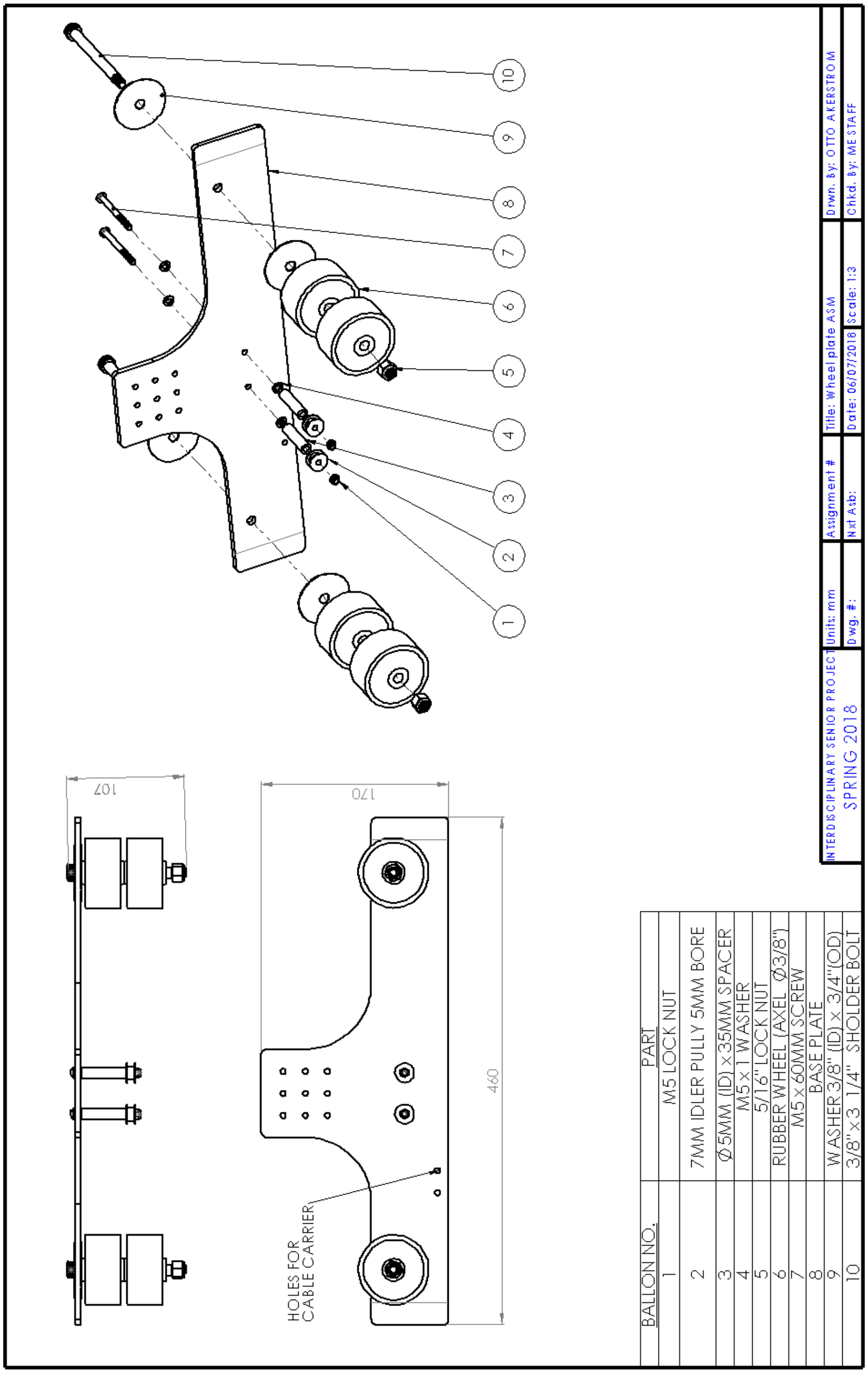
Appendix C5: Wheel Base Plate



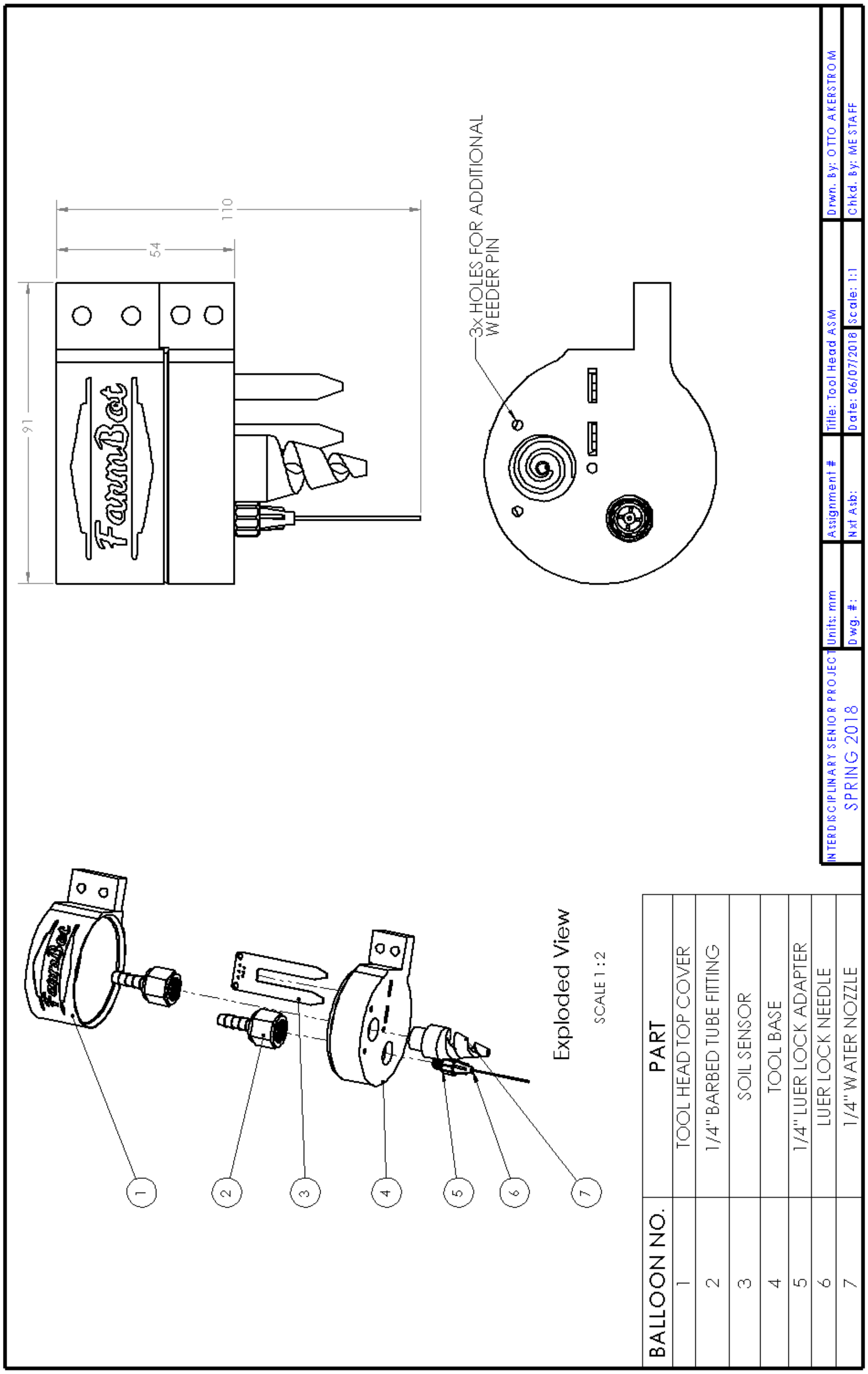
Appendix C6: Tool Base



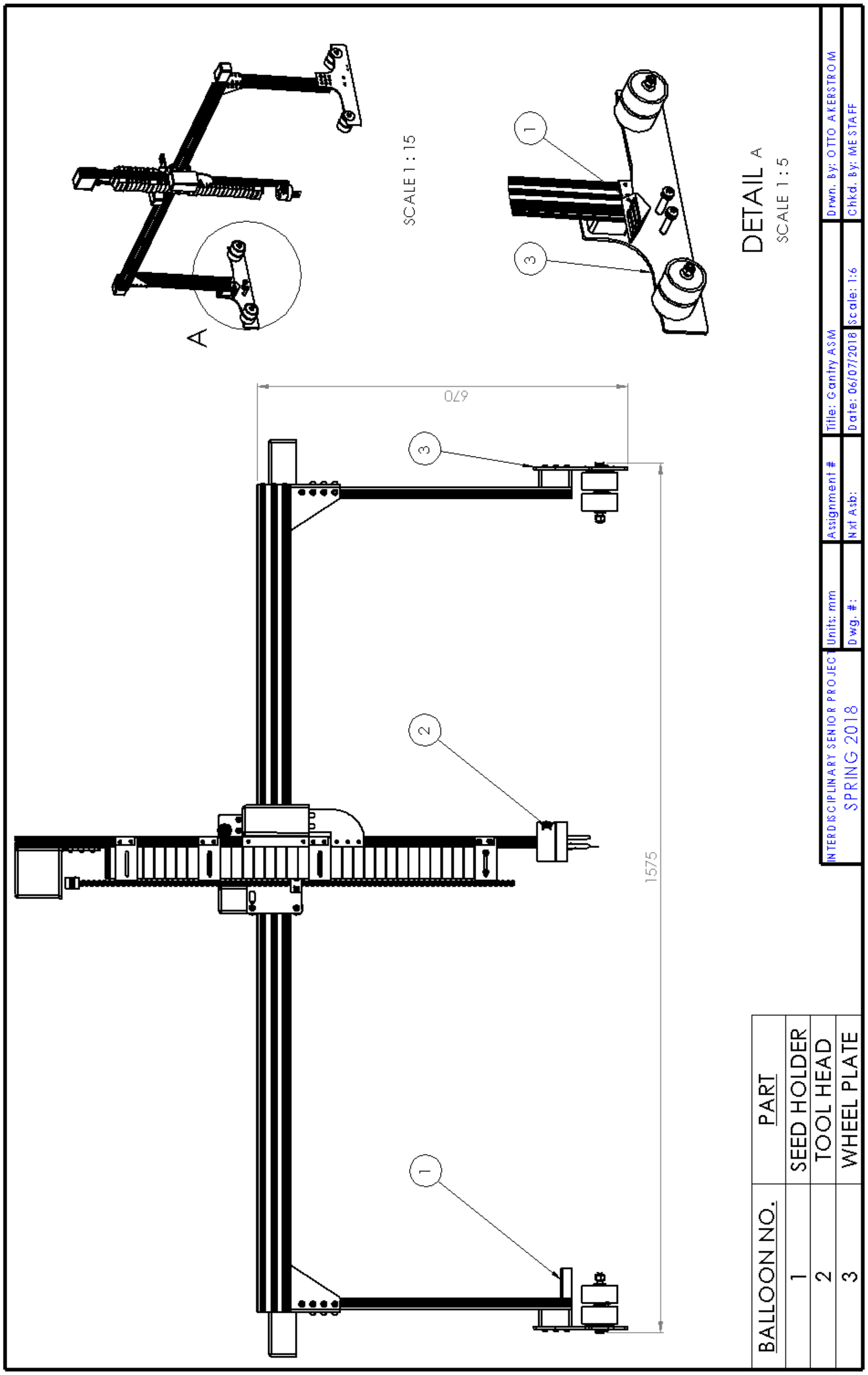
Appendix C7: Wheel Plate Assembly



Appendix C8: Tool Head Assembly



Appendix C9: Full Gantry to Show Scale



Appendix D: Vendor and Cost Information

	Supplier	Price	# of units	Total Price	Comments
Existing Wheel Plates					
Gantry Wheel Plates	BigBlueSaw	$25.00	2	$50.00	
V-wheels	OpenBuilds	$4.00	18	$72.00	
Bearings	OpenBuilds	$2.50	36	$90.00	
M5 shim	OpenBuilds	$0.25	18	$4.50	
M5 x30mm screws	McMasterCarr	$0.30	18	$5.40	
6mm spacer	OpenBuilds	$0.20	10	$2.00	
M5 washer	McMasterCarr	$0.05	18	$0.90	
M5 locknut	McMasterCarr	$0.15	18	$2.70	
6mm eccentric spacer	OpenBuilds	$2.00	8	$16.00	
M5 x10mm screws	McMasterCarr	$0.15	18	$2.70	
M5 tree nuts	McMasterCarr	$0.40	18	$7.20	
			182	$253.40	

		Price	# of units	Total Price	Comments
New Wheel Plates					
Wheel Plates	BigBlueSaw	$32.00	2	$64.00	
Rubber Wheels with ball bearings 2.5x1.25"	McMasterCarr	$6.62	4	$26.48	
3/8 shoulder bolts	McMasterCarr	$2.77	4	$11.08	
smooth idler pulleys	OpenBuilds	$5.99	4	$23.96	
40mm spacers	McMasterCarr	$2.01	4	$8.04	
nylon spacers	McMasterCarr	$1.71	4	$6.84	
tee nuts	McMasterCarr	$0.40	18	$7.20	
M5x40mm screws	McMasterCarr	$0.43	18	$7.74	
washers	McMasterCarr	$0.24	8	$1.92	
delrin spacer	Emco Plastics	$30.00	2	$60.00	
m5 washer	OpenBuilds	$0.05	4	$0.20	
			72	$217.46	

	Supplier	Price	# of units	Total Price	Comments
Other Gantry Parts					
gantry columns	OpenBuilds	$15.00	2	$30.00	
gantry corner brackets	BigBlueSaw	$30.00	2	$60.00	
M5 x10mm screws	McMasterCarr	$0.15	20	$3.00	
M5 tree nuts	McMasterCarr	$0.40	20	$8.00	
NEMA 17 Stepper Motor wit	Alibaba	$60.00	2	$120.00	
horizontal motor housings	ShapeWays	$10.00	2	$20.00	
M3 x10mm screws	McMasterCarr	$0.15	8	$1.20	
GT2 Timing Belts (4.5m)	OpenBuilds	$40.00	2	$80.00	
20 tooth GT2 Pulleys with s	OpenBuilds	$6.00	2	$12.00	
Belt Clips	BigBlueSaw	$3.00	2	$6.00	
			62	$340.20	

	Supplier	Price	# of units	Total Price	Comments
New Gantry Parts					
gantry columns	OpenBuilds	$15.00	2	$30.00	
gantry corner brackets	BigBlueSaw	$30.00	2	$60.00	
M5 x10mm screws	McMasterCarr	$0.15	20	$3.00	
M5 tree nuts	McMasterCarr	$0.40	20	$8.00	
NEMA 17 Stepper Motor v	Alibaba	$60.00	2	$120.00	
horizontal motor housings	Shapeways	$10.00	2	$20.00	
M3 x10mm screws	McMasterCarr	$0.15	8	$1.20	
GT2 Timing Belts (4.5m)	OpenBuilds	$40.00	2	$80.00	
14 tooth GT2 timing pulley	OpenBuilds	$5.00	2	$10.00	
Belt Clips	BigBlueSaw	$3.00	2	$6.00	
			62	$338.20	

	Supplier	Price	# of units	Total Price	Comments
Tracks					
Track Excursions	OpenBuilds	$30.00	4	$120.00	
Track End Plates	BigBlueSaw	$12.00	4	$48.00	
Track Joining Plates	OpenBuilds	$15.00	2	$30.00	
Wood Screws 25mm	Home Depot	$1.75	1	$1.75	
M5 10mm screws	McMasterCarr	$0.15	42	$6.30	
M5 Tee Nuts	McMasterCarr	$0.40	42	$16.80	
Horizontal Cable Carrier	Inventables	$50.00	1	$50.00	
belt clip	BigBlueSaw	$3.00	4	$12.00	
Timing Belt	OpenBuilds	$40.00	2	$80.00	
Cable supports	Shapeways	$3.00	11	$33.00	
			113	$397.85	

		Supplier	Price	# of units	Total Price	Comments
	New Track Parts					
Home Depot	Wood Screws		$1.75	1	$1.75	
Shapeways	cable support		$3.00	11	$33.00	
Inventables	cable carrier		$50.00	1	$50.00	
OpenBuilds	timing belt		$40.00	2	$80.00	
BigBlueSaw	belt clip and end stop		$15.00	4	$60.00	
				19	224.75	

	Supplier	Price	# of units	Total Price	Comments
Existing Toolhead					
barbs	McMasterCarr	$6.00	3	$18.00	
barb adapter	McMasterCarr	$2.00	1	$2.00	
o rings	McMasterCarr	$0.50	3	$1.50	
grommets	McMasterCarr	$0.50	4	$2.00	
luer lock adapter	McMasterCarr	$5.00	1	$5.00	
needles	McMasterCarr	$3.00	6	$18.00	
Soil Sensor	SparkFun	$6.00	1	$6.00	
jumpers	McMasterCarr	$0.50	3	$1.50	
links	McMasterCarr	$0.25	4	$1.00	
plug	McMasterCarr	$1.00	1	$1.00	
toolheads	Protolabs	$7.00	7	$49.00	
UTM	Shapeways	$30.00	1	$30.00	
cover	Protolabs	$10.00	1	$10.00	
water bottom	Protolabs	$5.00	1	$5.00	
magnets	Apex	$3.00	18	$54.00	
springs	Amazon	$0.50	7	$3.50	
blades	Protolabs	$2.00	12	$24.00	
60mm zip	McMasterCarr	$0.05	50	$2.50	
100mm	McMasterCarr	$0.07	25	$1.75	
			149	$235.75	

	Supplier	Price	# of units	Total Price	Comments
New Toolhead					
cover	Protolabs	$10.00	1	$10.00	
grommets	McMasterCarr	$0.50	3	$1.50	
plug	McMasterCarr	$1.00	1	$1.00	
tool mount	Protolabs	$10.00	1	$10.00	
nozzle	McMasterCarr	$16.57	1	$16.57	
tube adapters	McMasterCarr	$6.89	2	$13.78	
luer lock	McMasterCarr	$0.80	1	$0.80	
needles	McMasterCarr	$3.00	6	$18.00	
blades	Protolabs	$2.00	4	$8.00	
soil sensor	SparkFun	$6.00	1	$6.00	
Seed Holder	Protolabs	$10.00	1	$10.00	
			22	$95.65	

Appendix E: Component Specification Sheets

Description: Vendor supplied component specifications and data sheets.

Part	Part Number	Qty.	Cost/Part	Total Cost
Water-Resistant Rubber Wheel with Ball Bearing, 2-1/2" Diameter x 1-1/4" Wide	2829T15	4	$ 6.62	$ 26.48

Wheel Type	Tread on Core
Wheel/Tread Material	TPE Rubber
Wheel	
Diameter	2 1/2"
Width	1 1/4"
Hub Length	1 1/2"
Capacity per Wheel	140 lbs.
Hardness Rating	Soft
Hardness	Durometer 65A
Tread Shape	Flat
Wheel Color	Gray
Nonmarking Wheels	Yes
Wheel Bearing Type	Ball
Wheel Bearing Seal Type	Open
Wheel Bearing Material	Steel
Wheel Core	
Style	Closed
Material	Polypropylene Plastic
Temperature Range	-45° to 120° F
For Surface Type	Asphalt, Bar Grating, Brick, Concrete, Hardwood, Linoleum, Steel, Tile
For Use With	Mild Acids
For Axle Diameter	3/8"

Made of TPE rubber, these wheels outlast standard rubber wheels with better resistance to water, steam, and acids. Wheels have a rubber tread for quiet rolling and shock resistance with a hard polypropylene core for strength.

Ball bearings are the easiest to roll.

7mm Smooth Idler Pulley

The OpenBuilds Smooth Idler Pulley Wheel is an easy to assemble idler free wheel that can be used with Timing Belt up to 9mm wide.
"*This idler pulley can be mounted in a variety of fashions to fit your design; it can be plate mounted as well as direct V-Slot Linear Rail mounted using a Tee Nut and a Slot Washer.*"
Product Details

- Qty. 1
- Delrin
- Color: Black

Each Idler Pulley Kit Includes:

- (1) Precision Shim - 10x5x1mm
- (1) Nylon Insert Hex Locknut - M5
- (1) Low Profile Screw M5x25mm
- (1) Smooth Idler Pulley Wheel
- (1) Nylon Spacer - 1/8"
- (2) Ball Bearing 625 2RS 5x16x5

Note: Silicone lubrication is a great option for these Delrin wheels.

GT2-2M Timing Pulley- 14 Tooth

This is a high quality aluminum timing pulley that is perfect for your automation projects.
"This pulley is great for use in high resolution applications!"
Product Details

- Qty. 1
- GT2 (GT2-2M)
- Set Screws included (M3 - 5mm - 1.5mm)
- Pitch: 2mm
- OD: 12mm
- ID: 5mm
- Height: 14mm
- Belt Width: 1/4" and 6mm (up to 7mm)
- Bore Size: 5mm
- 2 Flanges with Hub
- Aluminum
- Color: Silver

5mmx35mm Spacers (10 pack)

Aluminum Spacers available in various, popular lengths and available in packs of 10, for your convenience.

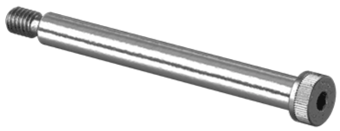
"We use one length of these versatile spacers to create a space between the Stepper Motor and the Motor Mounting Plate. This allows for room to mount hardware such as Flexible Couplings and Timing Pulleys to the motor shaft."

Product Details

- Qty. 10
- M5 ID
- Various Lengths
- OD 10mm
- Aluminum
- Color: Silver

Alloy Steel Shoulder Screw

3/8" Diameter 3-1/2" Long Shoulder, 5/16"-18 Thread



Shoulder Fit	Standard
Shoulder Diameter	3/8"
Shoulder Diameter Tolerance	-0.004" to -0.002"
Shoulder Length	3 1/2"
Shoulder Length Tolerance	-0.005" to 0.005"
Thread Size	5/16"-18
Screw Size Decimal Equivalent	0.313"
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 3A
Thread Direction	Right Hand
Thread Length	1/2"
Head Diameter	9/16"
Head Height	1/4"
Material	Alloy Steel
Finish	Black Oxide
Hardness	Rockwell C32
Tensile Strength	140,000 psi
Min. Shear Strength	84,000 psi
Head Type	Socket
Socket Head Profile	Standard
Head Texture	Knurled
Drive Style	Hex
Drive Size	3/16"
Specifications Met	ANSI/ASME B18.3, ASTM A574
System of Measurement	Inch
RoHS	Compliant

Button Head Hex Drive Screw

Passivated 18-8 Stainless Steel, M5 x 0.80 mm Thread, 60mm Long

Thread Size	M5
Thread Pitch	0.8 mm
Length	60 mm
Threading	Partially Threaded
Min. Thread Length	22 mm
Head Diameter	9.50 mm
Head Height	2.75 mm
Drive Style	Hex
Drive Size	3 mm
Material	Passivated 18-8 Stainless Steel
Hardness	Not Rated
Tensile Strength	70,000 psi
Thread Type	Metric
Thread Spacing	Coarse
Thread Fit	Class 6g
Thread Direction	Right Hand
Head Type	Rounded
Rounded Head Style	Button
Rounded Head Profile	Standard
System of Measurement	Metric
RoHS	Compliant

Made from 18-8 stainless steel, these button head screws have good chemical resistance and may be mildly magnetic. Length is measured from under the head.

Passivated stainless steel screws provide added protection against oxidation and corrosion.

Part	Part Number	Qty.	Cost/Part	Total Cost
Male Luer Lock x 1/4"-28 UNF (10 pack)	51525K221	1	$ 5.51	$ 5.51

For Use With	Air, Water
Shape	Straight
Type	Adapter
Coupling Type	Quick Turn
Quick-Turn Component	Plug
Flow Control	Open
Pipe Connection	
Type	Threaded
Gender	Male
Thread Size	1/4"-28
Thread Type	UNF
Material	Nylon Plastic
Maximum Pressure	45 psi @ 72° F
Maximum Vacuum	Not Rated
Temperature Range	-20° to 200° F
For Tube	
Material	PVC Plastic, Silicone Rubber
Hardness Rating	Soft
Hardness	Durometer A40-A65
Color	White
RoHS	Compliant

Made of plastic, these plugs are lighter than their metal counterparts. Also known as Luer Lock couplings, they connect with a half turn. They have a compact body for easy installation in tight spaces. Plugs are open-flow style, so there is no shut-off valve to stop the flow when the coupling is separated. They have a universal connection, so they will connect to any of the Plastic Quick-Turn Tube Sockets, regardless of the pipe or tube size.

Part	Part Number	Qty.	Cost/Part	Total Cost
Brass Full-Cone Spiral Spray Nozzle, 1/4" NPT	3282K54	1	$ 14.57	$ 14.57

Connection Type	Pipe
Pipe Connection Type	Threaded
Pipe Size	1/4
Thread Type	NPT
Gender	Male
Flow Rate, gpm	
@ 20 psi	1.8
@ 40 psi	2.6
@ 100 psi	4.1
@ 400 psi	8.2
Orifice Diameter	0.13"
Overall Width	9/16"
Length	1 7/8"
Maximum Pressure	400 psi
Maximum Temperature	450° F
Material	Brass
Tip Type	Permanent
Spray Application	High Volume
Spray Pattern	Full Cone
Spray Direction	Straight
For Use With	Thick Liquids, Thin Liquids
RoHS	Compliant

With a unique spiral design, these nozzles produce high flow rates and are clog-resistant. They are good for cooling, humidification, and dust- and foam-control applications. All provide a uniform distribution of droplets.

Brass nozzles have good corrosion resistance.

Part	Part Number	Qty.	Cost/Part	Total Cost
Adapter, 1/4" Tube ID to 1/4 NPSM	5372K212	1	$ 9.26	$ 9.26

For Use With	Air, Water
Shape	Straight
Type	Adapter
Tube Connection	
Type	Barbed
Gender	Male
For Tube ID	1/4"
Pipe Connection	
Type	Threaded
Thread Type	NPSM
Gender	Female
Swivel Type	Swivels Until Tightened
Pipe Size	1/4
Material	Nylon Plastic
Maximum Pressure	75 psi @ 72° F
Maximum Vacuum	Not Rated
Temperature Range	32° to 160° F
For Tube	
Material	Polyurethane, PVC Plastic
Hardness Rating	Firm, Soft
Hardness	Durometer A45-A80
Color	Semi-Clear White
Number of Barbs	Multiple
Clamps Required	Yes
RoHS	Compliant

These fittings have multiple barbs to grip onto tubing. They are made of nylon for excellent impact and abrasion resistance. Fittings that swivel until tightened allow for easy installation.

Part	Part Number	Qty.	Cost/Part	Total Cost
Adapter (Brass), 1/4" Tube ID to 1/4 NPTF	44555K125	2	$ 6.89	$ 13.78

For Use With	Air, Water
Shape	Straight
Type	Adapter
Tube Connection	
Type	Barbed
Gender	Male
For Tube ID	1/4"
Pipe Connection	
Type	Threaded
Thread Type	NPTF
Gender	Female
Pipe Size	1/4
Material	Brass
Maximum Pressure	100 psi @ 72° F
Maximum Vacuum	29 in. of Hg @ 72° F
Temperature Range	-65° to 75° F
For Tube	
Material	Polyurethane
Hardness Rating	Firm
Hardness	Durometer A95
Number of Barbs	Multiple
Clamps Required	Yes
RoHS	Not Compliant

These fittings are brass for good corrosion resistance.

NPTF (Dryseal) fittings are compatible with NPT threads.

Part	Part Number	Qty.	Cost/Part	Total Cost
Grommets	9600K33	4	$ 0.07	$ 0.28

For ID (A)	7/16"
For Material Thickness (B)	3/32"
ID (C)	3/8"
Flange Diameter (D)	5/8"
Overall Height (E)	9/32"
Material	SBR Rubber
Hardness	Durometer 55A
Temperature Range	-30° to 170° F
For Use Outdoors	No
For Use With	Wire, Cable, and Cords
Mount Type	Push In
Flexibility	Flexible
Color	Black
RoHS	Compliant

Push these flexible grommets into place to protect wires, cables, and cords by turning rough-edged and uneven holes into smooth, insulated holes.

Part	Part Number	Qty.	Cost/Part	Total Cost
Soil Moisture Sensor	SEN-13637	1	$ 4.95	$ 4.95

The SparkFun Soil Moisture Sensor is a simple breakout for measuring the moisture in soil and similar materials. The soil moisture sensor is pretty straightforward to use. The two large, exposed pads function as probes for the sensor, together acting as a variable resistor. The more water that is in the soil means the better the conductivity between the pads will be, resulting in a lower resistance and a higher SIG out. This version of the Soil Moisture Sensor includes a 3-pin screw pin terminal pre-soldered to the board for easy wiring and setup.

Appendix F: Team Contract

Team contract for PLANT3D

PLANT3D's Mission:

The mission of PLANT3D is to create a cheaper and more user friendly model of FarmBot that can be more affordable and accessible for non-technical customers specifically small home owners and K-8 school teachers. Our prototype will be completed by June 2018.

Team Name

This organization shall be known as PLANT3D.

Team Members

A. Members of the team include: Otto Akerstrom, Clayton Alderson, Cole Thomas, and Cailey Kamm.
B. No member shall represent the team unless authorized by the team.
C. Each member shall be provided a copy of the team contract with their signatures.

Member's Commitment

A. Members of the team commit to come to all meetings.
B. Vocalize clearly in a timely fashion when help is needed so that the project can move according to plan.
C. Committed to learn new skills and maintain open mindedness.
D. Committed to communicate in a timely fashion that will not obstruct project development.
E. Respect decisions reached via consensus.
F. Not be afraid or embarrassed when confused about any aspect of the project.

Decision Making

A. By Consensus: Everyone will agree with the decision before moving forward.

Team Interactions

A. All affairs of the team shall be governed by professional behavior with respect given to all team members.
B. Meetings shall be held thursday at 3:10 PM. **Additionally the team has agreed to meet Monday and Wednesday between 5-6pm if needed.**
C. Unless otherwise noted, all meetings will be held at Bonderson 104.
D. Special meetings of the team may be called by any team member.
E. Attendance is mandatory unless an approved excuse is made in advance.
F. Meeting discussions will be conducted in a conversational format with special regard for a dialogue that is respectful and considerate of all members in attendance.
G. A meeting agenda, distributed 1 days in advance, will guide meeting topics and timing.
H. The length of meetings shall be stated in advance.
I. All team members are expected to be punctual.
J. All meetings will be publicized to members using: phone calls, Group me, e-mail, and texting.
K. Notices shall be distributed not less than 1 days before the meeting date.
L. Violation of team rules will result in a team talk where an explanation is required?

Conflict Resolution

A. In the case of a conflict, the team will hold an intervention where both sides explains their point of view and compromise and move forward.
B. Resolutions will be made with a zero tolerance for aggression. Feelings will be expressed in a way that addresses how the subject feels rather than attacking the person he/she is in conflict with.
C. Interventions will be held at a time where neither subject is in a bad mood and can think clearly about the conflict. Ideally outside or somewhere off campus or mustang lanes where a beer can be enjoyed.
D. Failure to communicate tardiness will result in the member having to buy beer/pizza (under $20).

Roles and Responsibilities

A) Sponsor Contact: **Cole Thomas**
This team member will be the single point of contact for the sponsor in order to avoid any confusion regarding communication to/from the sponsor. The sponsor contact must communicate in a timely and professional manner with the sponsor.

Amendments

A. Amendments can be made but require a unanimous decision.

Effective Date

A. This contract of the PLANT3D team shall become effective on 09/28/2017.

B. Dates of amendment must be recorded in minutes of meetings at which amendments were approved, together with a revised set of bylaws.

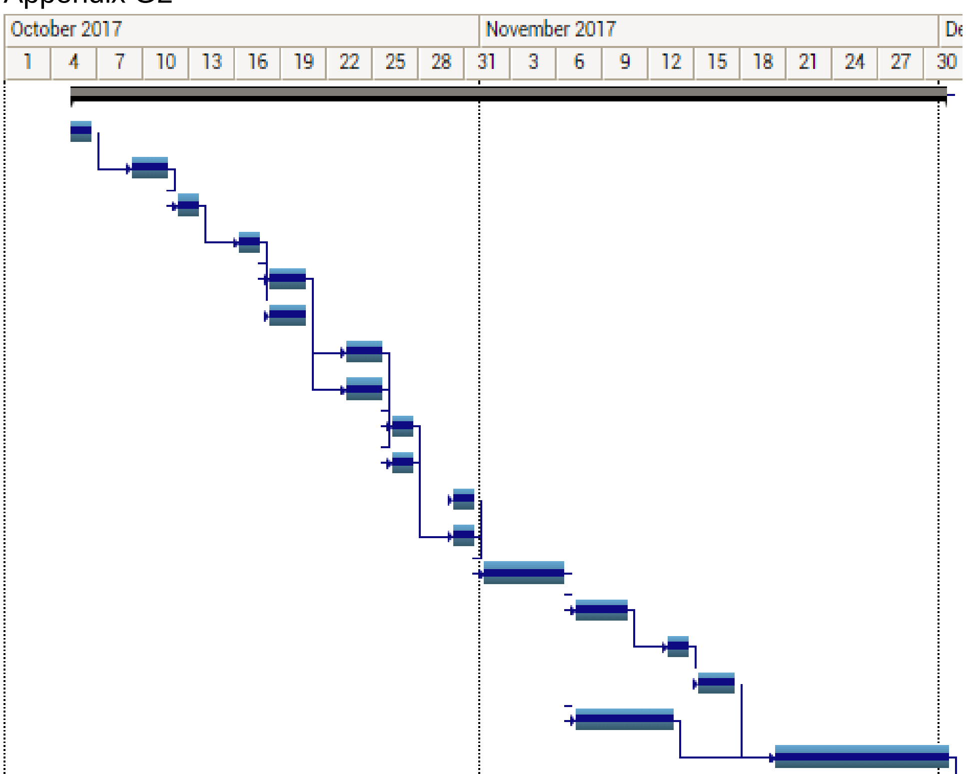
Appendix G: Project Gantt Chart

Appendix G1

1	✔	⊟ **Quarter 1**	42days	10/05/2017	12/01/2017	
2	✔	Initial FarmBot Research	2days	10/05/2017	10/06/2017	
3	✔	Design specification definition	3days	10/09/2017	10/11/2017	2
4	✔	specification checks	2days	10/12/2017	10/13/2017	3
5	✔	redesign of specifications	2days	10/16/2017	10/17/2017	4
6	✔	brainstorming of conceptual track designs	3days	10/18/2017	10/20/2017	5
7	✔	brainstorming of conceptual tool designs	3days	10/18/2017	10/20/2017	5
8	✔	initial prototyping of track	3days	10/23/2017	10/25/2017	6
9	✔	initial prototyping of toolhead	3days	10/23/2017	10/25/2017	7
10	✔	analysis of track prototypes/designs	2days	10/26/2017	10/27/2017	8
11	✔	analysis of tool head prototypes/designs	2days	10/26/2017	10/27/2017	9
12	✔	redesigning tool head prototypes	2days	10/30/2017	10/31/2017	10
13	✔	redesigning track prototypes	2days	10/30/2017	10/31/2017	11
14	✔	pro/con analysis of all prototypes	4days	11/01/2017	11/06/2017	13,12
15	✔	review designs with rory	4days	11/07/2017	11/10/2017	14
16	✔	decision matrix for prototypes	2days	11/13/2017	11/14/2017	15
17	✔	final selection for conceptual design	3days	11/15/2017	11/17/2017	16
18	✔	conceptual design research	5days	11/07/2017	11/13/2017	14
19	✔	conceptual design report	10days	11/20/2017	12/01/2017	17,18

Gantt chart tasks for quarter 1

Appendix G2



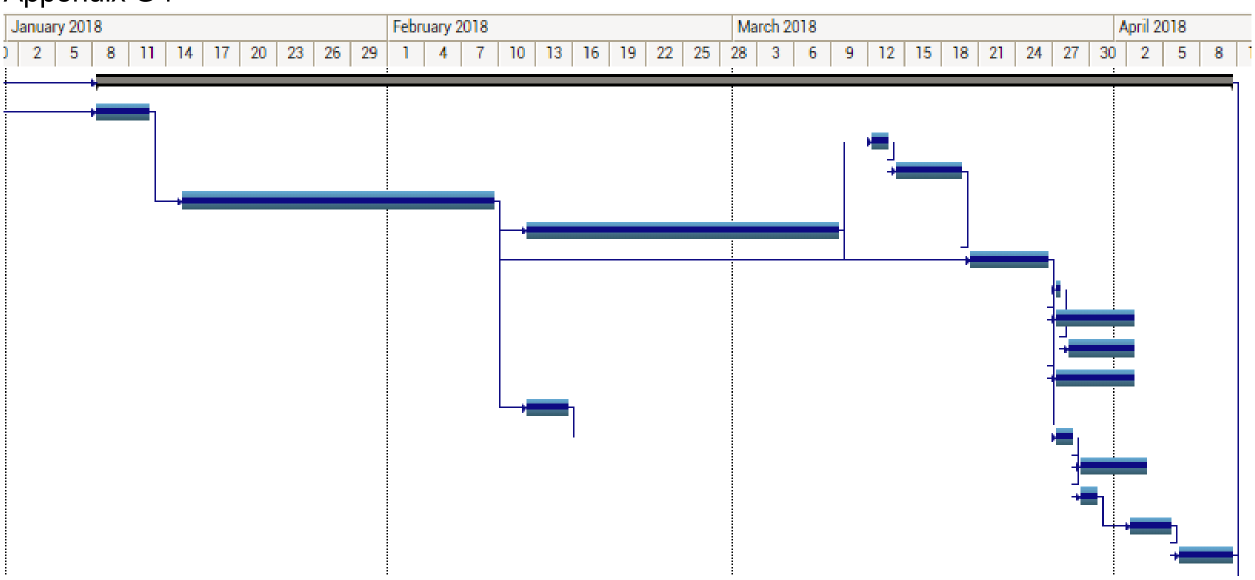
Gantt chart visualization for quarter 1

Appendix G3

20	✓	**QUARTER 2**	67days	01/08/2018	04/10/2018	1FS+25days
21	✓	functional Prototype conceptual design	5days	01/08/2018	01/12/2018	19
22	✓	Establish testing protocol	2days	03/12/2018	03/13/2018	25,21
23	✓	Build testing infrastructure	4days	03/14/2018	03/19/2018	22
24	✓	Build Functional Prototype	20days	01/15/2018	02/09/2018	21
25	✓	Begin Software development	20days	02/12/2018	03/09/2018	24
26	✓	test functional prototype	5days	03/20/2018	03/26/2018	25,23,24
27	✓	functional prototype demonstration	1day	03/27/2018	03/27/2018	26
28	✓	Functional analysis review	5days	03/27/2018	04/02/2018	26
29	✓	Sponsor input on review	4days	03/28/2018	04/02/2018	27
30	✓	analysis of functional prototype	5days	03/27/2018	04/02/2018	26
31	✓	analysis of prototype	4days	02/12/2018	02/15/2018	24
32	✓	redesign of prototype	2days	03/27/2018	03/28/2018	26,31
33	✓	test redesign	4days	03/29/2018	04/03/2018	32
34	✓	Test software	2days	03/29/2018	03/30/2018	32
35	✓	decide on final design	4days	04/02/2018	04/05/2018	34
36	✓	Fit software to Physical design	3days	04/06/2018	04/10/2018	35

Updated Gantt chart tasks for quarter 2

Appendix G4



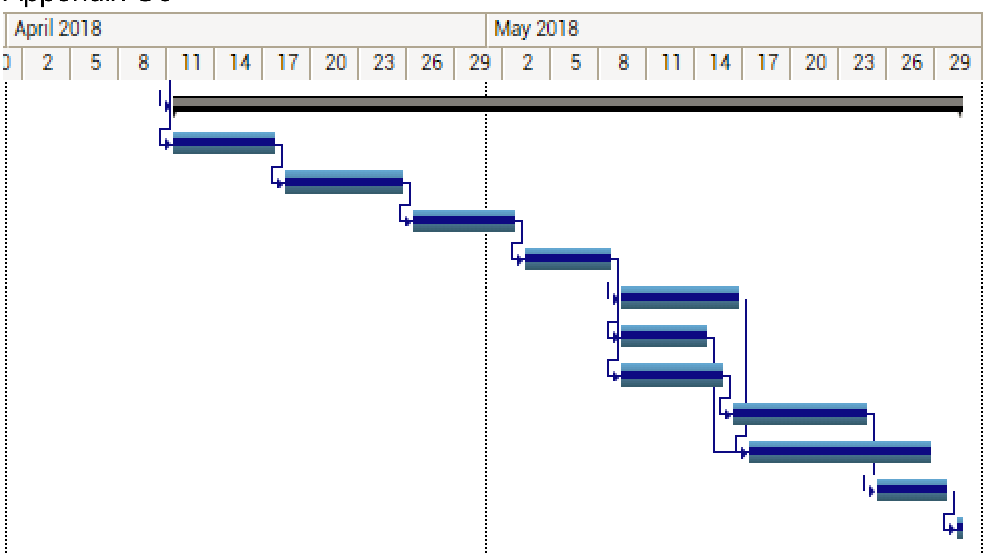
Updated Gantt chart visualization for quarter 2

Appendix G5

37	⊟ Quarter 3	36days	04/11/2018	05/30/2018	20
38	Finish FarmBot software to fit for physical design	5days	04/11/2018	04/17/2018	36
39	Test complete design	6days	04/18/2018	04/25/2018	38
40	analysis of complete design	5days	04/26/2018	05/02/2018	39
41	finalize changes for design	4days	05/03/2018	05/08/2018	40
42	Finish final build	6days	05/09/2018	05/16/2018	41
43	start project report	4days	05/09/2018	05/14/2018	41
44	analysis of customer specifications for final design	5days	05/09/2018	05/15/2018	41
45	review of project	7days	05/16/2018	05/24/2018	44
46	complete project write up	8days	05/17/2018	05/28/2018	42,43
47	Finish design for expo	3days	05/25/2018	05/29/2018	45
48	present at expo	1day	05/30/2018	05/30/2018	47

Updated Gantt chart tasks for quarter 3

Appendix G6



Updated Gantt Chart visualization for quarter 3

Appendix H: Safety Checklist

Y	N	
✓		Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	✓	Can any part of the design undergo high accelerations/decelerations?
	✓	Will the system have any large moving masses or large forces?
	✓	Will the system produce a projectile?
✓		Would it be possible for the system to fall under gravity creating injury?
	✓	Will a user be exposed to overhanging weights as part of the design?
	✓	Will the system have any sharp edges?
✓		Will all the electrical systems properly grounded?
✓		Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
✓		Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✓	Will there be any explosive or flammable liquids, gases, dust fuel part of the system?
	✓	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	✓	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✓	Can the system generate high levels of noise?
✓		Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc…?
✓		Will the system easier to use safely than unsafely?
✓		Will there be any other potential hazards not listed above? If yes, explain below?

Since Farmbot is on a raised bed there is a potential tripping hazard when harvesting.

Appendix I: Design Verification Plans and Report

DVP&R

Report Date | Sponsor | REPORTING ENGINEER:

Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED Quantity	SAMPLES TESTED Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	Assembly Time	Time people assembling the current subsystems and our subsystems	20% Reduction in total time	Cole	PV	2	C	6/2/2018	6/3/2018	46% reduction	2	0	The time saved here is mostly from toolhead set up time, some time was saved assembling tracks
2	# Parts for Tool Head	Count total parts in our final design	20% reduction in # of parts	Clayton	DV	1	B	5/30/2018	5/30/2018	85% Reduction	1	0	
3	# Parts for Tracks	Count total parts in our final design	20% reduction in # of parts	Clayton	DV	1	B	5/31/2018	5/31/2018	57% Reduction	1	0	
4	Cost to Consumer (To	Compile costs from current suppliers and vendors for new parts and compare with existing design.	20% reduction in cost	Otto	DV	1	B	5/31/2018	5/31/2018	59% Reduction	1	0	
5	Cost to Consumer (Tra	Compile costs from current suppliers and vendors for new parts and compare with existing design.	20% reduction in cost	Otto	DV	1	B	5/31/2018	5/31/2018	22% Reduction	1	0	
6	Precision	Track accuracy of each tool function using a FarmBot webapp design	Accurate to within 2cm	Cole	PV	200	C	5/31/2018	5/31/2018	Pass	193	7	Tooling only missed target on extreme cases with beyond worst case senarios
7	Parallel Track Allowance	Test functionality on a purposely built non parallel raised bed	Full functionality with 2cm of deviation	Otto	DV	10	B	5/29/2018	5/29/2018	5cm	10	10	Accuracy of the system is not significantly bad enough to lose functionality
8	Shipping Weight	Measure weights of new parts compared to old design.	10% Reduction	Cailey	DV	1	B	6/2/2018	6/2/2018	28% Reduction	1	0	Removing tracks resulted in the only significant chage
9	Shipping Size	Measure total packaging volume and compare to old packaging.	10% Reduction	Cailey	DV	1	B	6/2/2018	6/2/2018	~0% Reduction	0	1	Main gantry beam eliminates possibility of shrinking size without splitting beam into halves
10	Multi-Use	compare water, seed, soil sensing, and weeding to current system. Measuring accuracy of each function.	Full Functionality	Cole	PV	200	C	5/31/2018	5/31/2018	Pass	200	0	Failures were due to Z axis which was unchanged from original design
11	Clearance	Measure the lowest point when the Z-axis is at its highest point	0.5m from ground	Cailey	DV	1	B	5/25/2018	5/25/2018	>0.5m	1	0	New toolhead is slimmer than previous design
12	Functionality	Timing Belt strength	30 lb	Clayton	DV	2	B	5/25/2018	5/25/2018	Pass	3	0	All 3 Timing belts held over 40 lbs.
15	Functionality	Water nozzle pressure/ flow rate	15psi	Cole	CV	1	A	5/25/2018	5/25/2018	Pass	3	0	Nozzle works with current system

Appendix J: Manufacturing Images

Appendix J1 Tools in Cal Poly's Mustang 60, the Hangar, and Innovation Sandbox

Metal Disk Sander used to round corners of wheel plates.

Metal Vertical Bandsaw used to cut the stock to the rough dimensions for the belt clips and end stops.

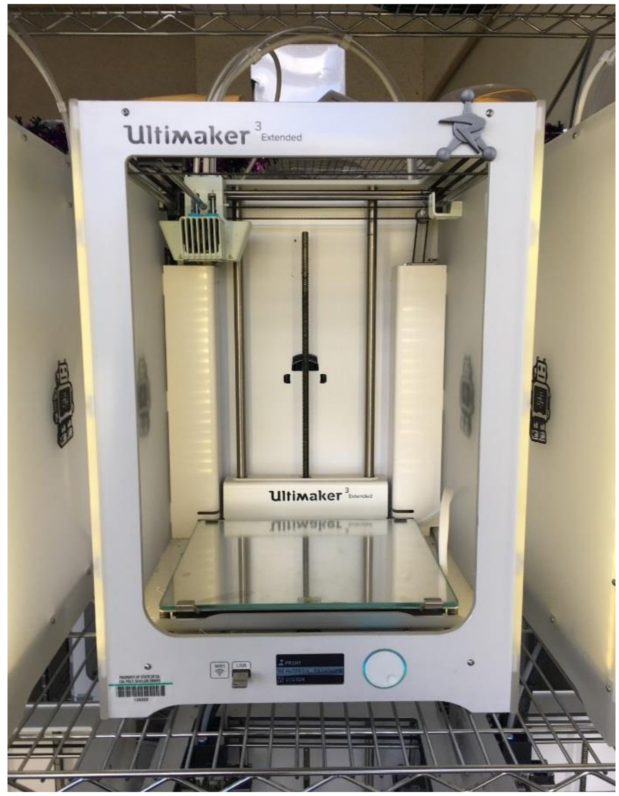
Drill Press used to drill the holes into the end stops.

Metal Belt Sander used to round the edges of the belt clips, and end stops and deburr edges.

Conical Deburring tool used to deburr holes in the wheel plates, and end stops.

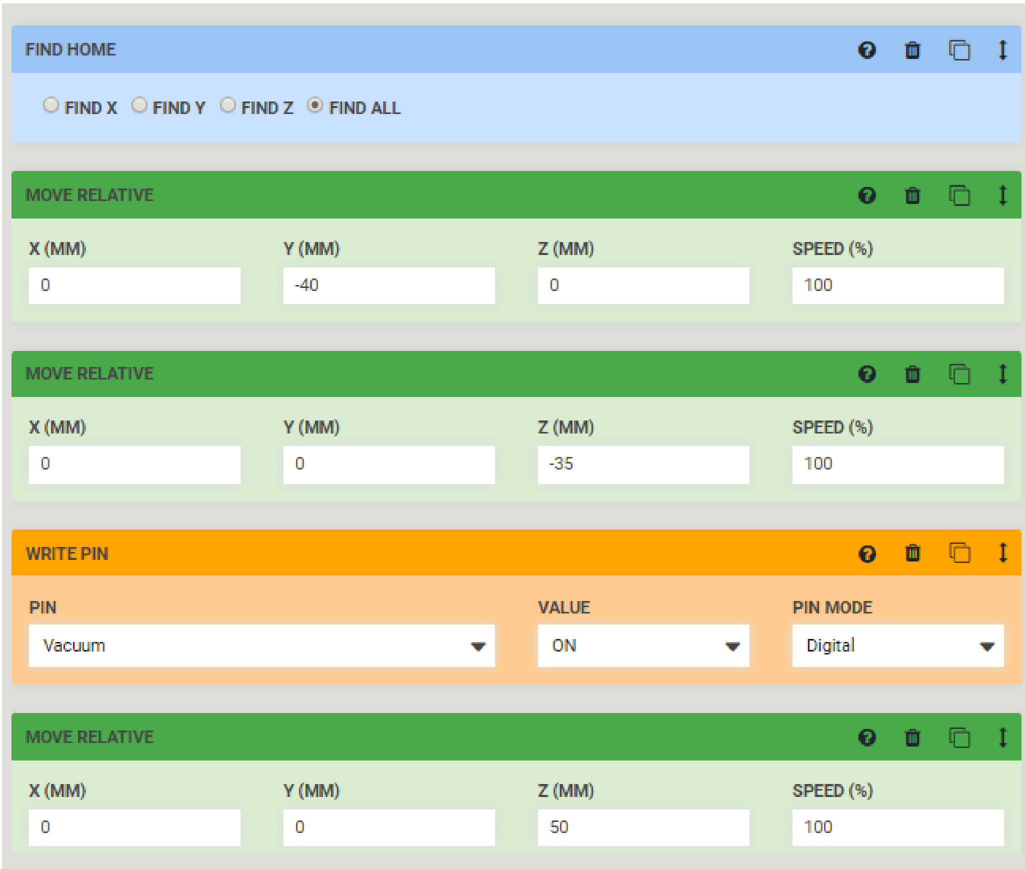
Micro-Mill used to make the adjustable Belt Clips.

Bridgeport Mill used to mill the rectangular spacers.

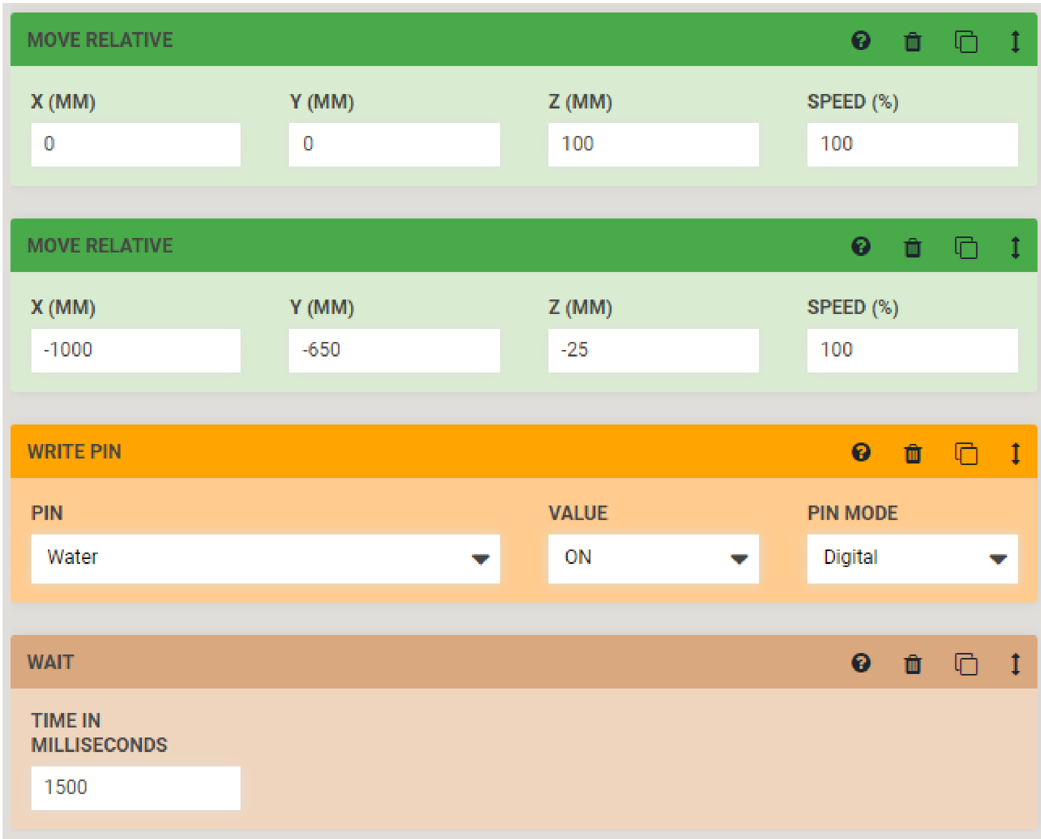


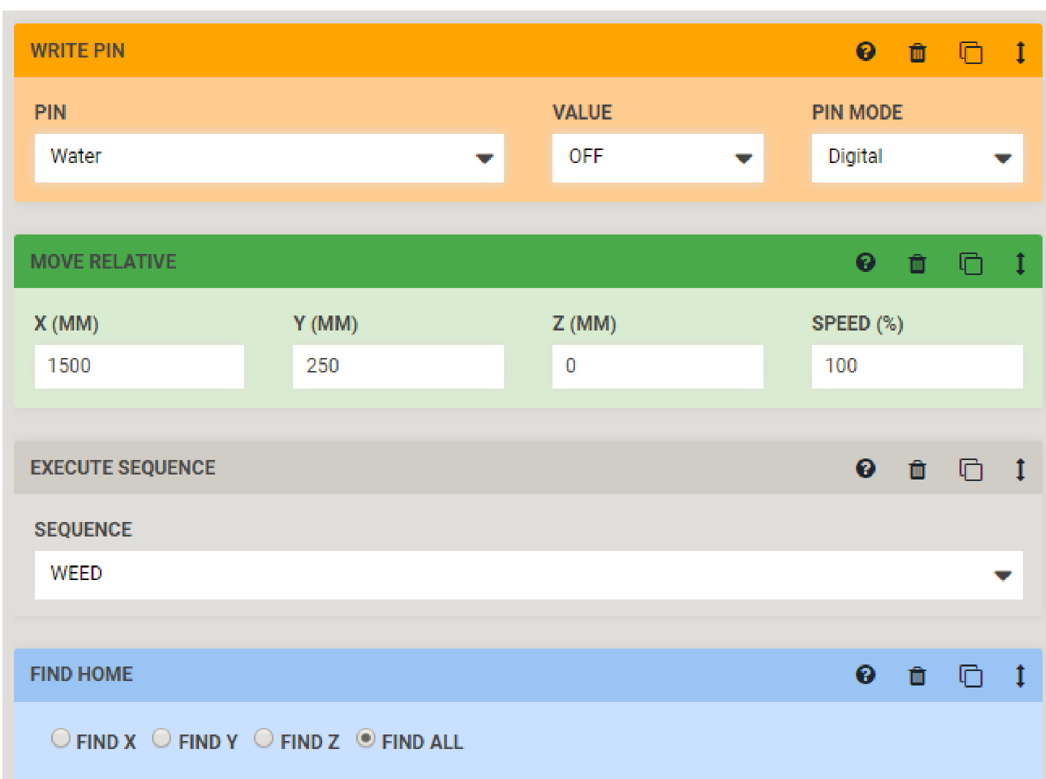
Ultimaker 3D Printer used to fabricate the tool head base and seed holder.

Appendix K: Test Sequencing




MOVE RELATIVE
X (MM) 1500
Y (MM) 750
Z (MM) 30
SPEED (%) 100
MOVE RELATIVE
X (MM) -30
Y (MM) -30
Z (MM) -150
SPEED (%) 100
MOVE RELATIVE
X (MM) 0
Y (MM) 0
Z (MM) -50
SPEED (%) 100
WRITE PIN
PIN Vacuum
VALUE OFF
PIN MODE Digital
MOVE RELATIVE
X (MM) 0
Y (MM) 0
Z (MM) 50
SPEED (%) 100
MOVE RELATIVE
X (MM) -250
Y (MM) 300
Z (MM) 0
SPEED (%) 100
MOVE RELATIVE
X (MM) 0
Y (MM) 0
Z (MM) -50
SPEED (%) 100
READ PIN
PIN Pin 59 (A5)
DATA LABEL Soil
PIN MODE Analog
SEND MESSAGE
MESSAGE 46/300
FarmBot read the soil sensor to be {{ pin59 }}
Info
TICKER NOTIFICATION
TOAST POP UP
EMAIL
SPEAK


MOVE RELATIVE
X (MM)
0
Y (MM)
0
Z (MM)
100
SPEED (%)
100
MOVE RELATIVE
X (MM)
-1000
Y (MM)
-650
Z (MM)
-25
SPEED (%)
100
WRITE PIN
PIN
Water
VALUE
ON
PIN MODE
Digital
WAIT
TIME IN MILLISECONDS
1500


WRITE PIN
PIN
Water
VALUE
OFF
PIN MODE
Digital
MOVE RELATIVE
X (MM)
1500
Y (MM)
250
Z (MM)
0
SPEED (%)
100
EXECUTE SEQUENCE
SEQUENCE
WEED
FIND HOME
FIND X
FIND Y
FIND Z
FIND ALL